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# The Old Halo metallicity gradient: the trace of a self-enrichment process

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**Abstract.** Based on a model of globular cluster self-enrichment published in a previous paper, we present an explanation for the metallicity gradient observed throughout the galactic Old Halo. Our self-enrichment model is based on the ability of globular cluster progenitor clouds to retain the ejecta of a first generation of Type II Supernovae. The key point is that this ability depends on the pressure exerted on the progenitor cloud by the surrounding protogalactic medium and therefore on the location of the cloud in the protoGalaxy. Since there is no significant (if any) metallicity gradient in the whole halo, we also present a review in favour of a galactic halo partly build via accretions and mergers of satellite systems. Some of them bear their own globular clusters and therefore "contaminate" the system of globular clusters formed "in situ", namely within the original potential well of the Galaxy. Therefore, the comparison between our self-enrichment model and the observational data should be limited to the genuine galactic globular clusters, the so-called Old Halo group.

**Key words:** Galaxy: evolution – Galaxy: formation – globular clusters: general – Galaxy: halo

## 1. Introduction

Galactic globular clusters (hereafter GCs) are fossil records of the formation of the Galaxy. The understanding of their formation process would certainly shed light on the early galactic evolution. However, at the present time, there is no widely accepted theory of GC formation. In Parmentier et al. (1999) (hereafter Paper I), we suggest a formation scenario based on a self-enrichment process such as proposed by Cayrel (1986) and further developed by Brown et al. (1991, 1995).

Our self-enrichment scenario takes place within the Fall & Rees (1985) description of the protoGalaxy, namely cold clouds embedded in a hot protogalactic background. These cold clouds are assumed to be the progenitors of galactic halo GCs. Since they are made up of primordial gas, the main advantage of a self-enrichment scenario is that it explains in parallel the formation of the clusters and the origin of their metal contents.

The main target of Paper I was to demonstrate conclusively that the gaseous progenitors of galactic halo GCs are able to sustain a few hundreds of Type II Supernovae (hereafter SNII) without being disrupted. This result is in contrast with the widespread idea according to which a few supernovae are able to disrupt a Proto-Globular Cluster Cloud (hereafter PGCC). Furthermore, the large number of SNeII allowed by our model can explain the amount of metals currently observed in galactic halo globular clusters, and this without any requirement of pre-enrichment of the gas.

The aim of the present paper is to explore further an interesting consequence of Paper I, which is also the main difference existing between our self-enrichment model and the one developed by Brown et al. (1995). The metallicity that a PGCC can reach through self-enrichment depends on the pressure exerted by the medium surrounding the progenitor cloud and, therefore, on the cloud location in the protoGalaxy. The deepest in the protoGalaxy the PGCC is located, the highest the final metallicity induced by self-enrichment will be. Therefore, we expect to find a metallicity gradient throughout the galactic halo.

The paper is organised as follows.
In Sect. 2, we briefly review the self-enrichment model presented in Paper I, focusing on the link between the final metallicity of the PGCC and the pressure exerted on it by the surrounding hot protogalactic background. In Sect. 3, we examine the different arguments suggesting the existence of halo substructures, in order to isolate to which one the self-enrichment model can be safely compared. In Sect. 4, we compare the model with the observations. Sect. 5 explores the putative link between GC metallicities and their perigalactic distances. Finally, we present our conclusions in Sect. 6.

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## 2. Self-enrichment model

According to Fall & Rees (1985), galactic halo GCs were formed during the collapse of the protoGalaxy. During this collapse, a thermal instability triggers the development of a two-phase structure, namely cold and dense clouds in pressure equilibrium with a hot and diffuse protogalactic background. The temperature of the clouds is assumed to remain at a value of $10^4$ K, where the cooling rate drops sharply in a metal-free medium. Their masses scale as the Jeans mass of a pressure-truncated spherical cloud with a temperature $\simeq 10^4$ K. Since this is of the same order of magnitude ($\simeq 10^6\,M_\odot$) as the GC masses, Fall & Rees (1985) identify these cold clouds with the progenitor clouds of GCs (however, this temperature, and therefore, the characteristic mass, is preserved only if there is a UV flux able to prevent any $H_2$ formation, the main coolant in a metal-free gas below $10^4$ K). As already mentioned, the PGCCs are assumed to be metal-free and the formation process must therefore explain how the metals are provided within each cloud. Within this context, the self-enrichment hypothesis was proposed by Cayrel (1986) and further developed by Brown et al. (1991, 1995). A first generation of stars is assumed to form in the central regions of the progenitor cloud. When the massive stars of this first generation explode as SNeII, all the cloud material is progressively swept in an expanding supershell. This supershell gets chemically enriched with the metals released by the exploding massive stars. Since it is a compressed layer of gas, it constitutes a dense medium where the formation of a second generation of stars is triggered. Under favourable conditions (see Brown et al., 1995) these second generation stars, formed in the chemically enriched supershell, can recollapse and form a GC. Therefore, the first generation SNeII provide the GC metals and trigger the formation of the GC stars.

Supernova energetics has been a major criticism of the GC self-enrichment hypothesis. However, the main target of Paper I was to conclusively demonstrate that a PGCC is not necessarily disrupted by SNII explosions. Our self-enrichment model is detailed in Paper I. Suffice it to say that we compute, for a given hot protogalactic background pressure, the supershell velocity during the sweeping of the PGCC as a function of the explosion rate. Based on this result, we compare the kinetic energy of the supershell with the binding energy of the PGCC in order to get the maximum number of SNeII the cloud is able to sustain.

Whatever the value of $P_h$, the pressure exerted by the hot protogalactic background on the cloud, we find that a PGCC can sustain about 200 SNeII. Such a large number of SNeII can provide the amount of metals observed in galactic halo GCs. The results of Paper I are summarized in Table 1 (see Sect. 4.2 for a justification of the $P_h$ values). Clearly, GC halo metallicities can be reached through self-enrichment.

**Table 1.** PGCC masses and metallicities for different values of the pressure of the medium confining the PGCCs.

| $P_{\rm h}$ [dyne.cm$^{-2}$] | $\log_{10}$ M/M$_\odot$ | [Fe/H] |
|---|---|---|
| $10^{-11}$ | 6.5 | -2.2 |
| $10^{-10}$ | 6.0 | -1.7 |
| $10^{-9}$ | 5.5 | -1.2 |

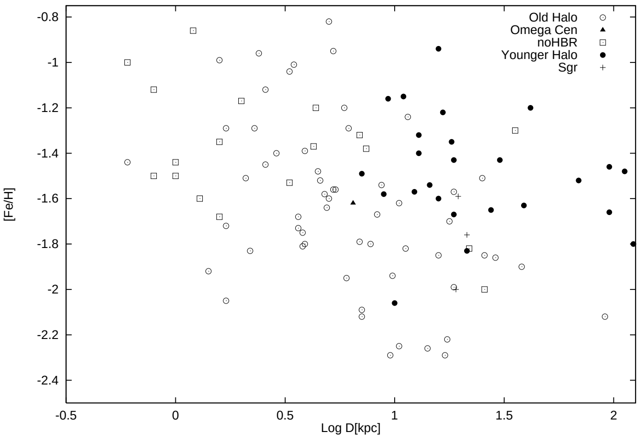


**Fig. 1.** The whole galactic Halo exhibits no clear-cut dependence of the metallicity on the galactocentric distance. It includes different subpopulations, such as the Old Halo and the Younger Halo. For the meaning of the different symbols, see Sect. 4.1. Data are based on Harris 1996

We see from Table 1 that the higher the external pressure is, the higher the metallicity will be. Indeed, since the dynamical constraint leads to a constant SNII number, assuming a given Initial Mass Function (namely a Salpeter one) and a given stellar mass range, a constant amount of metals (independent of $P_h$) is released by the first generation massive stars. Since the PGCC mass decreases with increasing external pressure (the Jeans mass scales as $P_h^{-1/2}$, Eq. (5) in Paper I), the PGCCs embedded in a higher pressure medium, namely located deeper in the protoGalaxy, reach higher final metallicities. This self-enrichment model, contrary to the one developed by Brown et al. (1995), implies a *metallicity gradient* throughout the galactic halo.

At first sight, there is no confirmation of this self-enrichment model by the observational data. The galactic halo exhibits no significant metallicity gradient (see Fig. 1; data are based on Harris 1996 [1]) However, according to Zinn (1993), the galactic halo is composed of *two distinct subpopulations of GCs* , what he calls an Old Halo and a Younger Halo. The next section presents a review of the evidence supporting Zinn's idea.

[1] Data updated 1999 June 22 at http://physun.physics. mcmaster.ca/Globular.html.

## 3. Two populations of galactic halo GCs

According to Zinn (1985), the galactic Globular Cluster System (hereafter GCS) includes two subsystems: the disk GCs [2] ([Fe/H] $> -0.8$) and the halo GCs ([Fe/H] $< -0.8$). Both groups also differ in their mean rotational velocity and spatial distribution about the galactic center.
Globular cluster classification has now gone a step further, and the halo subsystem could be itself divided into two groups.

### *3.1. Horizontal Branch morphology*

Zinn (1993) sorts the galactic halo GCs into two groups according to their Horizontal Branch (hereafter HB) morphology. The HB morphology, namely the colour distribution of the stars located along the HB, can be described by the index $C = (B - R)/(B + V + R)$ where B, V and R are respectively the numbers of blue, variables and red HB stars. This index therefore ranges from $-1$ for a purely red HB to $+1$ for a purely blue one. The morphology of the HB is essentially driven by the metallicity of the cluster. As such, [Fe/H] is the *first parameter* that governs the HB morphology. However, it has long been known that some clusters with similar [Fe/H] values present very different HB morphologies (e.g. M 13 and M 3, NGC 288 and NGC 362). This is the so-called *second parameter* effect: a second parameter (at least), in addition to metal abundance, is needed to explain the HB morphology.

Zinn (1993) notices that, while the inner halo GCs ($D < 8$ kpc, where $D$ is the galactocentric distance) exhibit a tight relationship between HB morphology and [Fe/H], the outer halo GCs ($D > 8$ kpc) show a large scatter in the same relation. Hence, the requirement of a second parameter to explain the HB morphology is mostly needed for GCs located beyond the solar circle. Since, at a given metallicity, these clusters have also redder HBs than the inner halo GCs, Zinn (1993) divides the galactic halo GCs into two groups: the inner halo GCs are classified as Blue Horizontal Branch (BHB) clusters, while the clusters whose HB types are 0.4 redder than their inner halo counterparts (equal metallicity) are labelled as Red Horizontal Branch (RHB) clusters. As mentioned above, these RHB clusters are mostly located outside the solar circle. This link between the influence of the second parameter and the galactocentric distance indicates that the second parameter problem must be related in some way to the formation of the Galaxy (Searle & Zinn 1978).

According to Lee et al. (1993), the most promising candidate for this second parameter is age. *If* age is indeed the second parameter, then, at a given metallicity, a RHB GC is younger than its BHB counterpart. Therefore, Zinn (1993) labels the BHB group and the RHB group respectively "Old" Halo and "Younger" Halo. To explain these putative age differences, and since the "Younger" Halo GCs are mostly located in the outer part of the halo, Zinn (1993) suggests that the two groups were formed in two different ways. The "Old" Halo (hereafter OH) GCs would have been formed during the rapid collapse of the protogalactic cloud, while the "Younger" Halo (hereafter YH) GCs would have been formed in satellite systems, such as dwarf galaxies, which evaded the protogalactic collapse and which were later accreted by the Galaxy.

[2] Due to their high concentration near the galactic center, these metal-rich clusters, at least those located within the inner ~4 kpc of the Galaxy, are now thought to be associated with the galactic bulge rather than with the disk (Minnitt 1995, Côté 1999).

### *3.2. GC Ages*

The hypothesis that RHB clusters are younger than their BHB counterparts relies on the implicit assumption that age is the only second parameter driving the HB morphology, in addition to metallicity. Therefore, it is interesting to wonder if age determinations based on the luminosity or the colour of the Main Sequence Turn-Off confirm such an hypothesis.

The nature of the second parameter remains a much debated question (for contrasting points of view, see the reviews by Stetson et al. 1996 and Sarajedini et al. 1997). Chaboyer et al. (1996) find that RHB clusters are on average 2-3 Gyr younger than BHB clusters, which is consistent with age being the dominant second parameter.
This point of view has been reinforced by other studies where some clusters have been found to be significantly younger than the bulk of the other galactic halo GCs. These are Pal 12 (Stetson et al. 1989), Rup 106 (Buonanno et al. 1993), Arp 2 (Buonanno et al. 1995), IC 4499 (Ferraro et al. 1995), Pyxis (Sarajedini & Geisler 1996), Pal 14 (Sarajedini 1997), Pal 5 (Buonanno et al. 1998), the outer halo GCs Pal 3, Pal 4, Eridanus (Stetson et al. 1999), NGC 362, 1261, 1851, 2808 (Rosenberg et al. 1999). All these younger GCs are RHB clusters and are located outside the solar circle, where the second parameter effect is dominant. Zinn's idea is therefore strengthened. However, according to Rosenberg et al. (1999), three RHB clusters (NGC 3201, NGC 5272 and possibly NGC 4590) have not been proven to be younger. As a result, age appears to be one of the most appealing second parameter candidates (Ferarro et al. 1995, Chaboyer et al. 1996, Stetson et al. 1999), but an additional parameter is probably at work in a minority of clusters.

### *3.3. Kinematic Differences*

Whatever the second parameter is, the concept of two genuinely distinct halo subsystems gets some support from the presence of a kinematic difference between the YH and the OH groups. While the mean galactic rotation of the

OH group is clearly prograde, it is close to zero, perhaps even sligthly retrograde, for the YH group (Zinn 1993, Da Costa & Armandroff 1995, Odenkirchen et al. 1997). This result has been recently confirmed by the work performed by Dinescu et al. (1999). Based on the most complete compilation of GC proper motions existing up to now, they compute the orbits of 38 GCs. Although a sharp truncation between the different orbital parameters does not appear, they show that, on the average, the "Old" Halo and the "Younger" Halo GCs exhibit some differences in their kinematics and their orbit shapes. The "Younger" Halo (RHB) group presents, *on the average*, a smaller rotational velocity, larger velocity dispersions, higher orbital energies, higher apogalactic distances ($D_{\rm a} \geq 10\,{\rm kpc}$) and higher excentricities than the "Old" Halo (BHB) group. If the RHB group represents an accreted component of our Galaxy, the mean rotational velocity suggests that a significant fraction of the outer GCs came from one or more ancestral objects on retrograde orbits.

### *3.4. Dwarf galaxies accretion*

Dwarf irregular and dwarf spheroidal galaxies, at least the most massive ones, also host their own GCS (e.g. the Magellanic Clouds, Fornax). Interestingly, in a plot of [Fe/H] vs C, the HB morphology index, some of the Large Magellanic Cloud (hereafter LMC) GCs fall among the outer halo GCs (Da Costa 1993). *If* age is accepted as the dominant second parameter, then these clusters are younger than the inner galactic halo GCs. This is in agreement with the presence in the LMC of young clusters whose masses are within the galactic GC mass range (Elson & Fall 1988, Meylan & Heggie 1997).
The hypothesis that the halo was partly built via accretion was underlined by several authors. Lin & Richer (1992) suggest that Rup 106 and Pal 12, two RHB clusters known to be younger than other GCs with similar metallicity (see Sect. 3.2), were tidally captured by the Galaxy from the Magellanic Clouds during their recent perigalacticon passage. A similar argument holds for Pyxis, another RHB and young cluster (Irwin et al. 1995). The association between some RHB/younger GCs and streams (alignments along great circles over the sky which could arise from the disruption of MW satellites) is advocated in Majewski (1994) and Fusi Pecci et al. (1995).

All these GCs could therefore have been born well apart from the original protoGalaxy, joining our Galaxy through later infall events. As such, they are *not indicative of the early formation of the galactic halo.*

Furthermore, Nature currently provides us with an example of satellite accretion. The Sagittarius dwarf spheroidal galaxy, the closest satellite of the Galaxy, is currently undergoing strong tidal distorsions indicating that it will probably be disrupted and absorbed by the Milky Way (Ibata et al. 1997, Johnston et al. 1999). Based on both positional and kinematic data, 4 GCs (M 54, Arp 2, Ter 8 with halo metallicities and Ter 7 with disk metallicity) unambigously belong to the Sgr dwarf (Ibata et al. 1997). These GCs are therefore being incorporated into the galactic halo and as such constitute a source of "contamination" of the genuine galactic GCs, the real tracers of the early evolution of the Galaxy.

Ibata et al. (1997) also strongly suspect the presence of a dark halo around the Sgr dwarf. Indeed, dwarf spheroidals are among the most dark-matter dominated systems known (Mateo 1998) and dwarf irregulars are significanly more dark-matter dominated than are large spirals (Carignan et al. 1990). The presence of dark matter halos around the Milky Way satellites, denser than what is found around large spirals, could induce some differences in the star and GC formation mechanisms compared to what occurs in the protoGalaxy (Larson 1993).

### *3.5. Spatial distribution*

Finally, considering the GCs with [Fe/H] $< -1$ (in order to remove the obvious disk clusters), Hartwick (1987) notes that their spatial distribution can be described in terms of two subsystems: an inner flattened distribution and an outer more spherical distribution.

### *3.6. What does this all mean ?*

The convergence of all the differences mentioned above (HB morphologies, ages, kinematic data, galactocentric distances and spatial distributions around the galactic center) between BHB and RHB GCs adds weight to the claim that they form two genuinely distinct groups. The existence of two main substructures in the galactic halo implies that a hybrid picture could conveniently describe its formation (Stetson et al. 1996, Sarajedini et al. 1997, Rosenberg et al. 1999). The inner part, populated by BHB GCs, would have been formed over a relatively short period of time during the collapse of the protoGalaxy (Eggen, Lynden-Bell & Sandage 1962), while the outer part, which includes most of the RHB GCs, was mainly built via accretion and mergers of satellite systems in a still ongoing process (Searle & Zinn 1978). In this case, the outer halo objects would actually bear little direct relevance to the formation history of the main part of the Galaxy. As such, they should not be considered when comparing our self-enrichment model to the observational situation (see Sect. 4.1).

To disentangle the *genuine* galactic GCs from those formed in satellite systems and accreted afterwards, Zinn (1993) suggests to rely on a HB morphology criterion. As illustrated above, this approach is indeed fruitful since many RHB clusters exhibit peculiarities, such as lower ages than their BHB counterparts. However, the GCSs of dwarf galaxies are not exclusively composed of young GCs and, consequently, the actual situation is certainly more complicated. A LMC cluster, Hodge 11, is as old as the inner halo GCs (Mighell et al. 1996). The Sagittarius cluster system will contribute to both the YH (Ter 7 and Arp 2) and OH (Ter 8 and M 54) groups (Da Costa & Armandroff 1995). Therefore, the OH subsystem may also contain some accreted objects and is not a pure sample of GCs formed during the collapse of the protoGalaxy main body. NGC 2419 and M 5 might be some of these interlopers. NGC 2419 is the only BHB GC located beyond the Magellanic Clouds. While it has the same age as M 92, an inner halo GC with similar metallicity (Harris et al. 1997), it is quite difficult to imagine that this metal-poor cluster formed in the inner halo and then migrated into the far outer one. The same problem stands for NGC 5904 (M 5), an outer halo BHB GC currently visiting the inner regions of the galactic halo (Dinescu et al. 1999). Clearly, Zinn's classification needs refinements but nevertheless constitutes a first step in understanding the different processes at work during the whole halo history. Therefore, in what follows, we mainly rely on this BHB/RHB division.

To close this section, we note that some of the trends presented by GCs are also reproduced by field halo stars.

1. According to Marquez & Schuster (1994), field halo stars whose apogalactocentric distances are larger than $\simeq 10$ kpc form a younger group with a larger age dispersion than the inner part of the stellar halo.
2. Majewski (1992) and Carney (1996) divide the stellar halo into a "high halo" sample of stars ($\langle|Z_{Max}|\rangle \geq$ 5 kpc, where $Z_{Max}$ is the maximum height reached by the stars above the galactic plane) and a "low halo" ($\langle|Z_{Max}|\rangle \leq 5$ kpc). The "high halo", which should be dominated by the accreted population, is found in net retrograde rotation. In contrast, the "low halo" is in prograde rotation.
3. Finally, Chiba (2000) notes that the stellar halo also includes subcomponents characterized by different density distributions: the outer part of the halo ($D >$ 15 kpc) appears to be nearly spherical, whereas the inner part exhibits a flattened distribution.

One interesting point is that the changes in these features occur more or less at the galactocentric distance where the fraction of RHB clusters increases significantly. The stellar halo pattern is therefore consistent with the halo GC dichotomy. This gives some support to the hypothesis of Jehin et al. (1999). Following them, field halo stars were, at least partly, formed in GCs from which they escaped through various dynamical processes (disruption or evaporation).

## 4. The metallicity gradient

### *4.1. Importance of the OH/YH division*

The whole galactic GCS exhibits a metallicity gradient interpreted as a disk-halo dichotomy, namely, the gradient is mainly driven by the high metallicity clusters (disk component: [Fe/H] $> -0.8$) located within $\simeq 8$ kpc from the galactic center (Djorgovski & Meylan 1994). The halo group itself ([Fe/H] $< -0.8$) presents no clear metallicity gradient (see Fig. 1). However, Sect. 3 provides several arguments supporting a further meaningful division, mainly based on a BHB/RHB (OH/YH) classification, of the halo system. As a result, the situation must be reconsidered.
Following Zinn (1993), the OH GCs are formed during the monolithic collapse of the protogalactic cloud while the more remote YH GCs are formed in fragments that escape the protogalactic collapse. Later on, these fragments evolve into satellite systems, e.g. dwarf galaxies, bearing their own GCs into the galactic halo once they are accreted by the Milky Way. These dwarf galaxies GCs are therefore added to the *original galactic* GCs.
According to the model exposed in Paper I, the metallicity [Fe/H], induced by the self-enrichment process, is related to the hot protogalactic background pressure $P_h$ by (see Table 1):

$$[\mathrm{Fe/H}] = 3.3 + 0.5 \log P_h \ . \tag{1}$$

Therefore, to a given pressure distribution of the hot protogalactic background, $P_h(D)$, corresponds a radial metallicity profile, [Fe/H]($D$). GCs whose progenitor clouds were not embedded in this pressure profile will corrupt the metallicity gradient if they are considered.
Since dwarf galaxy GCs were not born in the protoGalaxy, their progenitor clouds were not embedded in the same pressure profile as the galactic ones. Consequently, they must be rejected from any comparison between the theoretical results and the observational data.

In Fig. 1, the different types of GCs are marked by distinct symbols. OH and YH clusters are respectively represented by open and full circles (lists of OH and YH GCs are provided in Lee et al. 1994 and Da Costa & Armandroff 1995). The crosses label the 3 Sgr GCs with [Fe/H] $< -0.8$. The open squares ("noHBR" group) stand for the halo GCs for which the HB morphology index is not given in Harris (1996), probably because no color-magnitude diagrams precise enough to define the HB morphology index were available for these GCs. Indeed, most of them are located in the vicinity of the galactic center and, therefore, there is no reason to think that they belong to the accreted component of the Galaxy. The full triangle represents $\omega$ Cen, the most peculiar galactic GC (e.g. large mass, iron-peak element inhomogeneities in sharp contrast with the monometallicity observed in other GCs). These peculiarities could be the result of the merger of two GCs (Jurcsik 1998) or of the accretion of a dwarf galaxy tidally stripped of its stellar envelope (Majewski 2000).

Since the self-enrichment model applies to GCs formed in the proto-Milky Way all the progenitor clouds are embedded in a common pressure profile and we only consider the OH and noHBR groups. This subdivision of the halo GCs is important from the point of view of the existence or not of a metallicity gradient. In Fig. 2, we show [Fe/H] vs log$D$, limited to the OH and noHBR groups. By comparing Figs. 1 and 2, we see that the GC metallicity appears to be more strongly correlated with log$D$ once the presumed accreted component is removed. For the whole halo, the linear Pearson correlation coefficient is $-0.3$, corresponding to a probability of correlation of 99,85 %. Considering only the GCs shown in Fig. 2, this same coefficient improves to $-0.49$, corresponding to a probability of correlation larger than 99,999 %.
Median values of log$D$ in four metallicity bins are given in Table 2 for the OH+noHBR groups (the last column gives the number of clusters in each bin). The data in this table show a monotonic increase of $\langle \log D \rangle$ with decreasing metallicity over the range [Fe/H] $\simeq -0.8$ to [Fe/H] $\simeq -2.4$.

**Table 2.** Metallicity vs log$D$ for the OH+noHBR groups.

| [Fe/H] | $\langle \log D \rangle$ | n |
|---|---|---|
| $-1.2 \leq$ [Fe/H] $< -0.8$ | 0.41 | 13 |
| $-1.6 \leq$ [Fe/H] $< -1.2$ | 0.64 | 28 |
| $-2.0 \leq$ [Fe/H] $< -1.6$ | 0.89 | 25 |
| $-2.4 \leq$ [Fe/H] $< -2.0$ | 1.02 | 9 |

On the average, the more remote GCs are more metal-poor. This is in agreement with the self-enrichment model where the metallicity gradient is due to the decrease of the pressure exerted by the hot protogalactic background on the PGCCs as the galactocentric distance increases (see Table 1). To compare the theoretical metallicity gradient to the observational situation, one still needs an expression for the pressure profile $P_h(D)$ (see Eq. (1)).

### *4.2. Pressure profile of the hot protogalatic background*

Concerning this point, the situation is rather complex since there is obviously no agreement about the scaling of the $P_h(D)$ relation in the literature.

The luminous components of galaxies form through the collapse of gas in gravitationally dominant halos of dark matter. The density profile of such a halo is conveniently described as a singular isothermal sphere (White & Kauffmann 1994):

$$\rho(D) = \frac{V_c^2}{4\pi G}\frac{1}{D^2} \tag{2}$$

and

$$V_c^2 = \frac{GM(D)}{D} = const. \tag{3}$$

In these equations, $V_c$ is the circular velocity of the gas in the dark matter potential well of the Galaxy and G is the gravitational constant. Since we are mainly interested in the proto-Milky Way, the circular velocity $V_c$ is taken to be $220\,\mathrm{km\,s^{-1}}$ (Fall & Rees 1985).

Two timescales are important in determining the further evolution of the gas component within this halo of dark matter :

1. the dynamical (or free-fall) time:

$$\tau_{dyn} = \frac{D}{V_c}, \tag{4}$$

2. the radiative cooling timescale:

$$\tau_{cool} = \frac{3}{2}\frac{n_t kT}{n_i n_e \Lambda} \tag{5}$$

where $n_i$, $n_e$ and $n_t$ are respectively the ionic, electron and total number densities. k is the Boltzmann constant, $T$ is the gas temperature, and $\Lambda$ is the cooling function (Sutherland & Dopita 1993).

When $\tau_{dyn} < \tau_{cool}$, the gas undergoes quasi-static contraction, but once $\tau_{cool} < \tau_{dyn}$, the gas cloud can no longer maintain itself in quasi-static equilibrium and the collapse proceeds on a free-fall timescale (e.g. Rees & Ostriker 1977).

According to Fall & Ress (1985), during the collapse of the protoGalaxy a two-phase structure, namely cold clouds embedded in the remaining hot protogalactic background, grows in the collapsing gas. The hot component is depleted by the condensation of the cold clouds until its cooling and dynamical timescales are comparable. The hot gas is expected to remain near the virial temperature of the halo described by Eq. (2):

$$T_h = \frac{V_c^2}{2k}\mu_h m_H \simeq 1.7 \times 10^6\,\mathrm{K} \tag{6}$$

where $\mu_h$ is the mean molecular weight ($\sim 0.6$ for a primordial ionized plasma, with X $\simeq 0.76$ and Y $\simeq 0.24$). At this temperature, the value of the cooling function $\Lambda$ is $4.8 \times 10^{-24}$ $\mathrm{erg\,cm^3\,s^{-1}}$ (Sutherland & Dopita 1993). Combining Eqs. (4 - 6), we have

$$P_h = 5.3 \times 10^{-10} D_{kpc}^{-1}\ \mathrm{dyne\,cm^{-2}} \tag{7}$$

where $D_{kpc}$ is the galactocentric distance expressed in kpc. The corresponding metallicity gradient is therefore (dashed line in Fig. 2):

$$[\mathrm{Fe/H}] = -1.34 - 0.5 \log D_{kpc}\,. \tag{8}$$

In the Fall & Rees model, the hot component of the gas in which the PGCCs are embedded is at the virial temperature and has a density such that $\tau_{cool} \simeq \tau_{dyn}$. The model proposed by Murray & Lin (1992) is slightly different. It relies on the $\tau_{cool} \simeq \tau_{dyn}$ condition and also on the hypothesis of hydrostatic equilibrium for the hot gas:

$$\frac{1}{\rho_h}\frac{\mathrm{d}P_h}{\mathrm{d}D} = -\frac{V_c^2}{D}. \qquad (9)$$

The peculiarity of their model is that the rotation curve of the collapsing protoGalaxy is not assumed to be flat, but rather slightly decreasing with galactocentric distance. They argue that since the central regions, with the highest density, are the first to collapse, followed by regions from larger initial radii, the gravitational potential may be more centrally peaked than today. They adopt $V_c(D) \propto D^{-1/4}$. It should be noted that the value of the exponent ensures that the temperature of the hot gas obeys to Eq. (6) with $V_c$ and $T_h$ depending on $D$ (their Eq. (3.9)). In contrast with Fall & Rees (1985), their pressure profile for the hot protogalactic background scales as $D^{-2}$:

$$P_h = 1.25 \times 10^{-9} D_{kpc}^{-2}\ \mathrm{dyne\,cm^{-2}}. \qquad (10)$$

The corresponding metallicity gradient is therefore steeper (plain line in Fig. 2) than in Eq. (8):

$$[\mathrm{Fe/H}] = -1.15 - \log D_{kpc}\,. \qquad (11)$$

A third approach is suggested by Harris & Pudritz (1994). According to them, it is natural to expect that the hot and diffuse phase of the protoGalaxy is at the virial temperature and in hydrostatic balance with the isothermal dark matter potential well. Under these assumptions, the pressure distribution scales again as $D^{-2}$, $\tau_{dyn}$ and $\tau_{cool}$ scale respectively as $D$ (Eq. (4)) and as $D^2$ (Eq. (5)). There is thus a "critical" galactocentric distance $D_{crit}$ such that

- $\tau_{cool} < \tau_{dyn}$ when $D < D_{crit}$:
  no quasi-static equilibrium is possible;
- $\tau_{cool} \geq \tau_{dyn}$ when $D \geq D_{crit}$:
  the gas can remain in hydrostatic equilibrium.

In contrast to Fall & Rees (1985) and Murray & Lin (1992) models, there is no equality between $\tau_{cool}$ and $\tau_{dyn}$ over the whole galactic halo and, therefore, this property can no longer be used to determine $P_h(D)$. However, it is interesting to note that the steady rise of the ratio $\tau_{cool}/\tau_{dyn}$ with galactocentric distance is a property found in the halos of giant ellipticals, e.g. M 87 (Fabricant et al. 1980).

Murray & Lin (1992) and Harris & Pudritz (1994) give the same scaling law for the pressure distribution ($P_h \propto D^{-2}$), but not from the same hypotheses! This illustrates the difficulty to derive an expression for the metallicity gradient from the self-enrichment model.
In what follows we will use the results given by Eqs. (8) and (11).

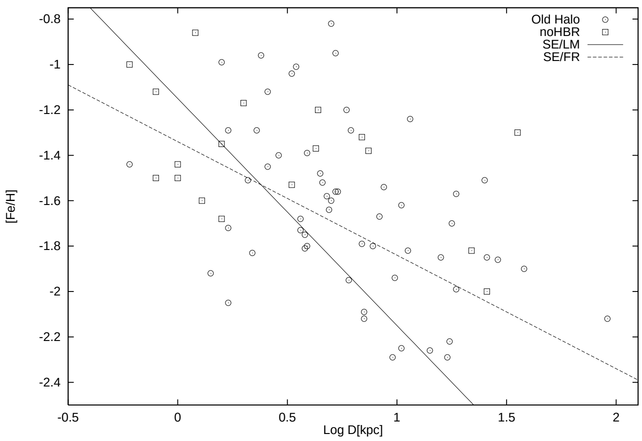


**Fig. 2.** Comparison between 2 theoretical [Fe/H] vs log$D$ relationships and the metallicity radial distribution function of the OH+noHBR groups. The plain and dashed curves represent the self-enrichment model combined with, respectively, the Murray & Lin (1992) and the Fall & Rees (1985) pressure profiles. GC symbols are identical as in Fig. 1

### *4.3. Discussion*

In Fig. 2, we compare the results given by Eq. (8) (dashed line) and Eq. (11) (plain line) to the observational data. The region of interest, namely where the bulk of the OH group is located, is the galactocentric range 1 to 30 kpc. The metallicity intervals predicted by Eqs. (8) and (11) for these values of the galactocentric distance are respectively [−2 dex, −1.35 dex] and [−2.65 dex, −1.15 dex]. The second model (self-enrichment model combined with $P_h \propto D^{-2}$, in this case the Murray & Lin (1992) pressure distribution) is a better description for the observed metallicity range (see Table 2).

The theoretical metallicity gradients corresponding to Eqs. (8) ($P_h \propto D^{-1}$) and (11) ($P_h \propto D^{-2}$) are respectively $\Delta[\mathrm{Fe/H}]/\Delta\log D = -0.5$ dex and $-1$ dex. It is not straightforward to compare these results with the observational gradient because of the rather high dispersion in the [Fe/H] vs log$D$ plot, partly due to measurement errors in [Fe/H] and log$D$. The observed dispersion can also be explained by the GC orbital motions. Indeed, our model predicts a relation between the GC metallicities and the galactocentric distances of their *formation site*. But the GCs were carried away from their formation sites through their orbital motions. The initial radial distribution of globular cluster abundances has therefore been modified but we can only use the current one. A least-squares fit to the OH+noHBR groups, which takes into account the uncertainties in both coordinates (Press et al. 1992), yields:

$$[\mathrm{Fe/H}] = (-1.35 \pm 0.26)\log D + (-0.64 \pm 0.24). \qquad (12)$$

If the noHBR clusters are not included, the slope of the least-squares fit is even steeper with a value of $-1.68 \pm$

0.41. The errors on [Fe/H] are assumed to be $\pm 0.15$ dex (King 1999). The errors on log$D$ are deduced from the comparison between the observational points and a "classical" least-squares fit to the log$D$ vs [Fe/H] plot with $\sigma_{\log D}$=1. This leads to an error of $\pm 0.4$ in log$D$. We caution that, by doing so, the errors are assumed to be normally distributed. This is probably not the case for log$D$, since the galactocentric distances of the formation sites are replaced by the current galactocentric distances. Therefore, the dispersion in log$D$ cannot be attributed solely to measurement errors. The slope of Eq. (12) is consistent with the one of Eq. (11) at the $1.3\sigma$ level, while it is different from the slope given by Eq. (8) at the $3.3\sigma$ level. As a conclusion, Eq. (1) better describes the observed radial distribution of GC metallicities when it is combined with a pressure profile scaling as $D^{-2}$ (Eq. (11)) rather than $D^{-1}$ (Eq. (8)). However, Eq. (11) somewhat underestimates the mean observed metallicity at a given galactocentric distance. This can be due to:

1. an underestimate by the self-enrichment model for the mass of metals ejected by the SNeII in the PGCCs (uncertainties in, e.g., the SNII yields, the high-mass stellar mass spectrum; see Paper I for a discussion of the second point);
2. an underestimate of the hot protogalactic background pressure;
3. the possibility that GCs formed deeper in the galactic potential well than their current location in the halo (see Sect. 5 for a related point).

In addition to the metallicity gradient, the model presents a second interesting consequence. According to Sarajedini et al. (1997), once the search for an age-metallicity relationship is restricted to the Old Halo group, there is no evidence for such a relation. This result is confirmed by the careful work carried out by Rosenberg et al. (1999). Their conclusion is consistent with a single mean value for the age, independent of [Fe/H][3] Clearly, a parameter other than the age is needed to explain the metallicity range observed in the OH/BHB group. The self-enrichment model provides us with such a parameter, namely the external pressure around the PGCCs. Combined with a pressure distribution scaling as $D^{-2}$, the model explains fairly nicely the galactic halo GC metallicities, without any requirement for an age-metallicity relation (in the usual sense of age decreasing with metallicity). The final proportion of heavy elements is mostly fixed by the pressure exerted by the medium surrounding the progenitor clouds.
If, in the future, the pressure distribution was proven to scale as $D^{-1}$ instead of $D^{-2}$, then this would mean that our model underestimates/overestimates the amount of chemical enrichment in the inner/outer regions of the halo.

Finally, the steady decline of the hot gas pressure with galactocentric distance should also lead to a gradient in the mass of the *PGCC* (see Table 1). That such a mass gradient could still be observable today is not a certainty. Indeed, the initial mass of the PGCCs undergoes changes due to various evolutionary processes:

a. The formation of the second stellar generation: there is no reason why this star formation episod would take place with the same star formation efficiency in each cloud.
b. Mass loss (evaporation): once they are formed, GCs undergo mass loss due to their interactions with the galactic gravitational field (Meylan 2000).

Evaporation and random star formation efficiency are sources of scatter in the relation between the PGCC and GC masses. In addition, mass determinations of GCs are still uncertain at least by a factor 2 (Meylan 2000). Therefore, and as pointed out by Brown (1993): "Even if the Jeans mass did play a role in the formation of GCs, it is unlikely that a one-to-one relationship exists between the *proto-cluster cloud* mass and the *present cluster* mass."
GC absolute visual magnitudes $M_v$ could also be used to search for a relic of the mass gradient since obtaining GC integrated luminosities is much easier than determining GC masses. However, the absolute visual magnitude is not an accurate estimation of the GC mass because of the scatter introduced by the mass-to-light ratios in the mass-luminosity relation. For instance, in the Pryor & Meylan (1993) compilation, the mass-to-light ratios of most of the OH GCs range from 1.1 to 3.8. Despite these various uncertainties, Brown (1993) finds a steady decline in $M_v$ for $D < 15$ kpc in a plot of average $M_v$ versus average log$D$ for the galactic halo clusters. Therefore, his conclusion further supports the hypothesis of an origin of galactic halo GCs in clouds having the Jeans mass.

## 5. Were GCs formed near their perigalacticon?

The initial halo metallicity gradient was severely altered by the accretion of GCs formed in dwarf and/or irregular galaxies. The genuine Milky Way GCs moving away from their formation sites is another cause of alteration. It would be very useful to know the galactocentric distances at which the GCs were formed, in order to better evaluate the validity of Eqs. (8) and (11).
In Sect. 4.3, it was suggested that GCs might have formed deeper in the galactic halo than their current location. However, we caution that this result relies on the self-enrichment model *and* on the assumed pressure distribution. Therefore, this outcome cumulates uncertainties from both and it certainly does not stand on a firm support. Even so, previous papers already suggest

[3] Again, the same pattern is observed for the field stars: there is no age-metallicity correlation for the FHS (Marquez & Schuster 1994).

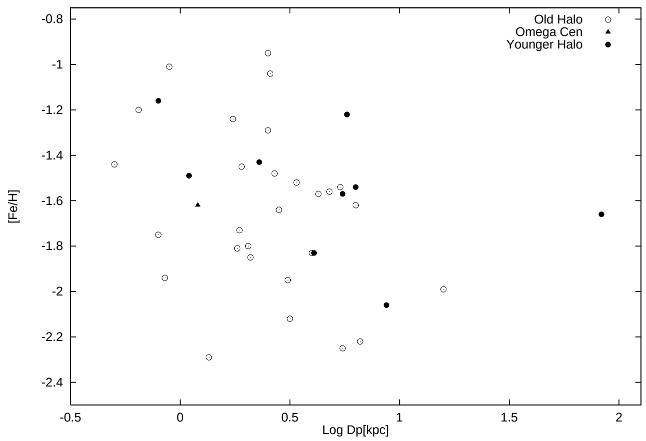


**Fig. 3.** Same as in Fig. 1 but the GC metallicities are plotted vs the perigalactocentric distances

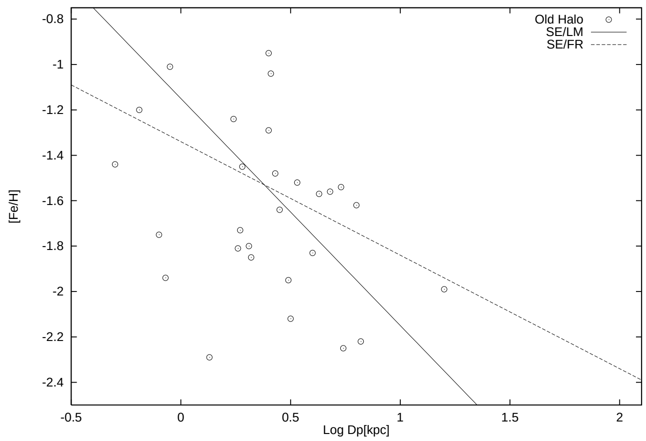


**Fig. 4.** Same as in Fig. 2 but the GC metallicities are plotted vs the perigalactocentric distances

that the correlation between [Fe/H] and log$D_p$, where $D_p$ is the perigalactocentric distance of the GCs, may be stronger than between [Fe/H] and log$D$.

Freeman & Norris (1981) notice "a clear gradient in the [Fe/H]-$D_p$ plane". According to them, this may be a hint that the clusters did form near perigalacticon. Van den Bergh (1995) also notes that the GC metallicity correlates somewhat more strongly with $D_p$ than it does with the present GC galactocentric distances. Nevertheless, the method used to derive these perigalactic distances is somewhat problematic. It assumes that the current GC tidal radius is mostly set by the galactic tidal field at the closest approach of the cluster to the galactic center, namely the perigalacticon (King 1962). As a result, tidal radii of well observed GCs are used to estimate their perigalactic distances. By so doing, the GC internal processes, especially the two-body relaxation, are neglected (Meziane & Colin 1996). These internal processes lead to a replenishment of the outer regions of the cluster between two perigalactic passages and therefore modify the outer radius set at the perigalacticon. Thus, it is dangerous to rely on the current outer radius of GCs to derive their perigalactocentric distances. In order to avoid this problem, perigalactic distances derived from the computation of GC orbits (Dinescu et al. 1999) are used in Figs. 3 (all GCs with known perigalactic distances) and 4 (OH GCs). Another cluster, NGC 6522 (Terndrup et al. 1998), is added to Dinescu's list. The sample is by far smaller than in Van den Bergh (1995). This is due to the necessity to know the proper motions in order to compute the GC orbits in a given galactic potential.

The (log$D_p$, [Fe/H]) plot (Fig. 4) does not appear tighter than the (log$D$, [Fe/H]) one (Fig. 2). The linear Pearson correlation coefficient in Fig. 4 is only $-0.31$, corresponding to a probability of correlation of the order of 90 %. In contrast, considering the (log$D$, [Fe/H]) plot for the same sample of GCs, the correlation coefficient is still $-0.43$, corresponding to a probability of correlation of 96 %. The orbits only provide evidence that the more metal-rich halo clusters ([Fe/H] $> -1.4$) are concentrated towards the galactic center ($D_p < 3$ kpc). Therefore, these new data do not really confirm the suggestion made by Freeman & Norris (1981). New perigalactic distances would be helpful to give a definitive answer to the existence of a link between the perigalactocentric distances and the metallicities of galactic halo GCs.

## 6. Conclusions

The self-enrichment model of galactic halo GCs (see Paper I for a detailed description) has been compared to the observational situation and the conclusions are as follow:

1. The final metallicity induced by the self-enrichment process depends on $P_h$, the pressure exerted on the PGCC by the hot protogalactic background medium. The result is in agreement with galactic halo GC metallicities.
2. There is a range of halo GC metallicities due to the variations in $P_h$ with the galactocentric distance. Considering the clusters located between 1 and 30 kpc, the ranges of metallicities [Fe/H] are 0.75 and 1.50 dex when the self-enrichment model is combined with $P_h \propto D^{-1}$ and $P_h \propto D^{-2}$ respectively. The second solution is in better agreement with the observed metallicity range. Moreover, when the Murray & Lin (1992) pressure distribution is used, the theoretical metallicity interval over the galactocentric range $1 \leq D_{kpc} \leq 30$ is $-2.65 \leq$ [Fe/H] $\leq -1.15$. This result is in nice agreement with the observations in the galactic halo GCs.
3. Because of the expected decrease in $P_h$ with increasing galactocentric distance, the model induces a metallicity gradient throughout the galactic halo. Such a metallicity gradient is indeed observed once the GCs

suspected to have been accreted by the Milky Way are removed. These clusters were born in fragments which evaded the initial protogalactic collapse and have experienced their own chemical evolution. The division between the galactic and accreted components of the halo is mainly based on the BHB/RHB (OH/YH) classification introduced by Zinn (1993). Indeed, it seems likely that the halo GCs consist of clusters with more than one origin. Since the accreted clusters did not take part in the formation and early evolution of the galactic halo, their progenitor clouds did not share the same external pressure distribution as the genuine galactic proto-GCs. Therefore, they should not be taken into account in the self-enrichment model.
Again, the observed radial distribution of GC abundances favours a background pressure profile scaling as $D^{-2}$ rather than $D^{-1}$.
However, it should be noted that the scatter of the data about the model lines in Fig. 2 (and also in Fig. 4) exceeds the observational uncertainties. As already stated, this can be due to the GC orbital motions which carry them away from their formation sites. Furthermore, it is certainly an oversimplification to consider that $P_h$ is the only parameter determining the GC metallicity. Other parameters must interfere (e.g. stellar mass range, SNII yields, ...).
4. In our model, no age-metallicity relation is required to explain the different GC metallicities. Actually, there is no compelling evidence for an age-metallicity relationship among halo GCs (Buonanno et al. 1998), and especially once the sample is limited to the BHB/OH group (Sarajedini et al. 1997). In this group, all GCs are coeval according to Rosenberg et al. (1999). This is in agreement with our self-enrichment model where we see an enhanced chemical enrichment with decreasing galactocentric distance rather with time.

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