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The self-enrichment of galactic halo globular clusters :

a clue to their formation ?

G. Parmentier, E. Jehin, P. Magain*, **C. Neuforge, A. Noels and A.A. Thoul****

Institut d'Astrophysique et de Géophysique, Université de Liège, 5, Avenue de Cointe, B-4000 Liège, Belgium

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Abstract. We present a model of globular cluster self-enrichment. In the protogalaxy, cold and dense clouds embedded in the hot protogalactic medium are assumed to be the progenitors of galactic halo globular clusters. The massive stars of a first generation of metal-free stars, born in the central areas of the proto-globular cluster clouds, explode as Type II supernovae. The associated blast waves trigger the expansion of a supershell, sweeping all the material of the cloud, and the heavy elements released by these massive stars enrich the supershell. A second generation of stars is born in these compressed and enriched layers of gas. These stars can recollapse and form a globular cluster. This work aims at revising the most often encountered argument against self-enrichment, namely the presumed ability of a small number of supernovae to disrupt a proto-globular cluster cloud. We describe a model of the dynamics of the supershell and of its progressive chemical enrichment. We show that the minimal mass of the primordial cluster cloud required to avoid disruption by several tens of Type II supernovae is compatible with the masses usually assumed for proto-globular cluster clouds. Furthermore, the corresponding self-enrichment level is in agreement with halo globular cluster metallicities.

Key words: globular clusters: general – Galaxy: evolution – supernovae: general – ISM: bubbles – population III

Send offprint requests to: G. Parmentier

* Maître de Recherches au Fonds National de la Recherche Scientifique (Belgium)

** Chercheur qualifié au Fonds National de la Recherche Scientifique (Belgium)

1. Introduction

The study of the chemical composition and dynamics of the galactic halo components, field metal-poor stars and globular clusters (hereafter GCs), provides a natural way to trace the early phases of the galactic evolution. In an attempt to get some new insights on the early galactic nucleosynthesis, accurate relative abundances have been obtained from the analysis of high resolution and high signal-to-noise spectra for a sample of 21 mildly metal-poor stars (Jehin et al. 1998, 1999). The correlations between the relative abundances of 16 elements have been studied, with a special emphasis on the neutron capture ones. This analysis reveals the existence of two sub-populations of field metal-poor stars, namely Pop IIa and Pop IIb. They differ by the behaviour of the s-process elements versus the α and r-process elements. To explain such correlations, Jehin et al. (1998, 1999) have suggested a scenario for the formation of metal-poor stars which closely relates the origin of these stars to the formation and the evolution of galactic globular clusters.

At present, there is no widely accepted theory of globular cluster formation. According to some scenarios, GC formation represents the high-mass tail of star cluster formation. Bound stellar clusters form in the dense cores of much larger star-forming clouds with an efficiency of the order 10^{-3} to 10^{-2} (Larson, 1993). If GCs form in a similar way, the total mass of the protoglobular clouds should therefore be two or three orders of magnitude greater than the current GC masses, leading to a total mass of $10^8 M_\odot$. Harris and Pudritz (1994) have investigated the GC formation in such clouds which they call SGMC (Super Giant Molecular Clouds). The physical conditions in these SGMC have been further explored by McLaughlin and Pudritz (1996a).

Another type of scenarios rely on a heating-cooling balance to preserve a given temperature (of the order of 10^4K) and thus a characteristic Jeans Mass at the protogalactic epoch. In this context, Fall and Rees (1985) propose that GCs would form in the collapsing gas of the protogalaxy. During this collapse, a thermal instability triggers the development of a two-phase structure, namely cold clouds in pressure equilibrium with a hot and diffused medium. They assume that the temperature of the cold clouds remains at 10^4K since the cooling rate drops sharply at this temperature in a primordial gas. This assumption leads to a characteristic mass of order 10^6 $M_\odot$ for the cold clouds. However, this temperature, and therefore the characterictic mass, is preserved only if there is a flux of UV or X-ray radiation able to prevent any H_2 formation, the main coolant in a metal-free gas below 10^4K. Provided that this condition is fullfilled, and since the characteristic mass is of the order of GC masses (although a bit larger, but see section 5.2.1), Fall and Rees identify the cold clouds with the progenitors of GCs. Several formation scenarios have included their key idea : cloud-cloud collisions (Murray and Lin 1992), self-enrichment model (Brown, Burkert and Truran 1991, 1995).

According to the scenario suggested by Jehin *et al.* (1998, 1999), GCs may have undergone a Type II supernovae phase in their early history. This scenario appears therefore to be linked with the self-enrichment model developed by Brown *et al.* within the context of the Fall and Rees theory. Following Jehin *et al.*, thick disk and field halo stars were born in globular clusters from which they escaped either during an early disruption of the proto-globular cluster (Pop IIa) or through a later disruption or evaporation process of the cluster (Pop IIb). The basic idea is that the chemical evolution of the GCs can be described in two phases. During phase I, a first generation of metal-free stars form in the central regions of proto-globular cluster clouds (hereafter PGCC). The corresponding massive stars evolve, end their lives as Type II supernovae (hereafter SNeII) and eject α, r-process and possibly a small amount of light s-process elements into the interstellar medium. A second generation of stars form out of this enriched ISM. If the PGCC get disrupted, those stars form Pop IIa. If it survives and forms a globular cluster, we get to the second phase where intermediate mass stars reach the AGB stage of stellar evolution, ejecting s elements into the ISM through stellar winds or superwind events. The matter released in the ISM by AGB stars will be accreted by lower mass stars, enriching their external layers in s elements. During the subsequent dynamical evolution of the globular cluster, some of the surface-enriched low-mass stars evaporate from the cluster, become field halo stars and form PopIIb.

Others studies have already underlined the two star generations concept : Cayrel (1986) and Brown et al. (1991, 1995) were pioneers in this field. Zhang and Ma (1993) have demonstrated that no single star formation can fit the observations of GCs chemical properties. They show that there must be two distinct stages of star formation : a self-enrichment stage (where the currently observed metallicity is produced by a first generation of stars) and a starburst stage (formation of the second generation stars).

These two generations scenarios were marginal for a long time. Indeed, the major criticism of such globular cluster self-enrichment model is based on the comparison between the energy released by a few supernova explosions and the PGCC gravitational binding energy : they are of the same order of magnitude. It might seem, therefore, that proto-globular cluster clouds (within the context of the Fall and Rees theory) cannot survive a supernova explosion phase and are disrupted (Meylan and Heggie, 1997). Nevertheless, a significant part of the energy released by a supernova explosion is lost by radiative cooling (Falle, 1981) and the kinetic energy fraction interacting with the ISM must be reconsidered.

While Brown et al. (1991, 1995) have mostly focused on the computations of the supershell behaviour through hydrodynamical computations, we revisit some of the ideas that have been used against the hypothesis of GC self-enrichment. In this first paper, we tackle the questions of the supernova energetics and of the narowness of GC red giant branch. Dopita and Smith (1986) have already addressed the first point from a purely dynamical point of view. In their model, they assume the simultaneity of central supernova explosions and they use the Kompaneets (1960) approximation to describe the resulting blast wave motion. During this progression from the central regions to the edge of the PGCC, all the material encountered by the blast wave is swept up into a dense shell. They demonstrate that, when the shell emerges from the cloud, its kinetic energy, based on the number of supernovae that have exploded, is compatible with the gravitational binding energy of a cloud whose mass is more or less $10^7 M_{\odot}$. When the kinetic energy of the emerging shell is larger than the binding energy of the initial cloud, this cloud is assumed to be disrupted by the SNeII. There is therefore a relation between the cloud mass and the maximum number of supernovae it can sustain without being disrupted. However, a $10^7 M_{\odot}$ cloud is more massive than the PGCCs considered within the Fall and Rees theory.

We derive here a similar relation based on the supershell description (Castor, McCray, Weaver, 1975) of the central supernova explosions. Contrary to the Kompaneets approximation, this theory allows us to take into account the existence of a mass spectrum for the massive supernova progenitors and, therefore, the spacing in time of the explosions. In addition to the above dynamical constraint, we also establish a chemical one. For a given mass of primordial gas, we compute the maximum number of supernovae the PGCC can sustain and the corresponding self-enrichment level at the end of the supernova phase. We show that the metallicity reached is compatible with the metallicity observed in galactic halo globular clusters.

The paper is organized as follows. In section 2, we review the observations gathered by Jehin et al. (1998, 1999) and the scenario proposed to explain them. In section 3, we describe the PGCCs, the first generation of metal-free stars, and the supershell propagation inside PGCCs due to SNeII explosions. In section 4, we show that the disruption criterion proposed by Dopita and Smith (1986), here computed with the supershell theory, gives the correct globular cluster metallicities. In section 5, we discuss the sensitivity of our model to the first generation IMF parameter values and we examine the implications of an important observational constraint, the RGB narrowness noticed in most globular cluster Color Magnitude Diagrams (CMDs). Finally, we present our conclusions in section 6.

2. The EASE scenario

2.1. Observational results

Jehin et al. (1998, 1999) selected a sample of 21 unevolved metal-poor stars with roughly one tenth of the solar metallicity. This corresponds to the transition between the halo and the disk. All stars are dwarfs or subgiants, at roughly solar effective temperature and covering a narrow metallicity range. High quality data have been obtained and a careful spectroscopic analysis was carried out. The scatter in element abundances reflects genuine cosmic scatter and not observational uncertainties. Abundances of iron-peak elements (V, Cr, Fe, Ni), α elements (Mg, Ca, Ti), light s-process elements (Sr, Y, Zr), heavy s-process elements (Ba, La, Ce), an r-process element (Eu) and mixed r-,s-process elements (Nd, Sm) have been determined. Among these data, Jehin et al. (1998, 1999) have found correlations between abundance ratios at a given metallicity. If some elements are correlated, they are likely to have been processed in the same astrophysical sites, giving fruitful information about nucleosynthesis. The following results were obtained (Jehin et al. 1999) :

a. there is a one-to-one correlation between the r-process element Eu and the α element Ti : most points are located on a single straight line with a slope $\simeq 1$ ending with a clumping at the maximum value of [Ti/Fe]
b. looking for correlations including s-process element (e.g. yttrium), two distinct behaviours were found : some stars show a correlation between [Y/Fe] and [Ti/Fe] with a slope smaller than one while some others stars have a constant (and maximum) [Ti/Fe] value and varying values of [Y/Fe], starting at the maximum value reached by the first group. This vertical branch is the counterpart of the previous clump. We have labeled this diagram the *two-branches diagram*(Fig. 1). Since our sample contains a limited number of stars, we have added results from other analysis concerning metal-poor stars ($-2 <$ [Fe/H] < -0.6). All these metal-poor stars follow the same trend independently of their metallicity. But if we now add results for disk stars of various metallicities, the relation obtained for metal-poor stars is no more verified : the points scatter in the upper-left part of the diagram. There is a change of behaviour at a metallicity [Fe/H]$\simeq -0.6$. The *two-branches diagram* describes a relation that applies only to metal-poor stars. Higher metallicity stars do not fit the *two-branches diagram* .

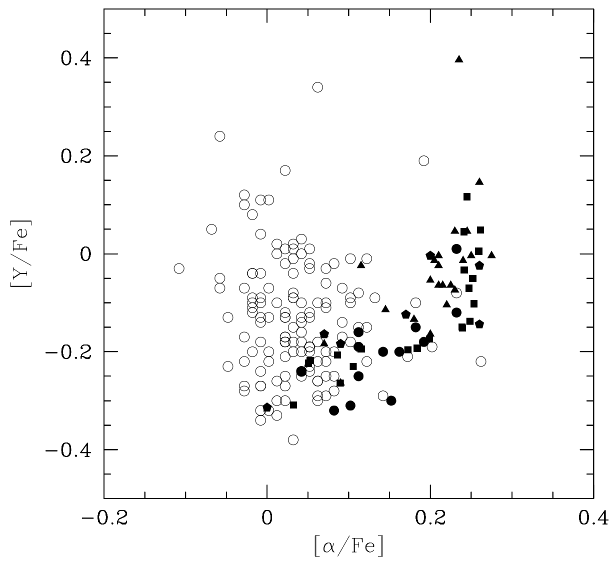

Fig. 1. Correlation diagram for [Y/Fe] versus [α/Fe] with the data from Jehin et al. (1999) (full squares), the data of Nissen and Schuster (1997) (full triangles), the data of Zhao and Magain (1991) (full pentagon), the data of Edvardsson et al. (1993) for [Fe/H]< -0.6 (full circles) and for [Fe/H]> -0.6 (open circles). The zero points have been fixed by comparing the results obtained for the stars in common with Jehin et al. (1999)

2.2. Interpretation : two-phases globular cluster evolution

We associate the two branches of the diagram with two distinct chemical evolution phases of globular clusters, namely a SNII phase (phase I) and an AGB wind phase (phase II).

Phase 1

We assume the formation of a first generation of stars in the central regions, the densest ones, of a proto-globular primordial gas cloud. The most massive stars of this first generation evolve and become supernovae, ejecting α and r-process elements into the surrounding ISM. These supernova explosions also trigger the formation of an expanding shell, sweeping all the PGCC material encountered during its expansion and decelerated by the surrounding ISM. In this supershell, the supernova ejecta mix with the ambient ISM, enriching it in α and r-process elements. The shell constitutes a dense medium since it contains all the PGCC gas in a very thin layer (a few tenths of parsecs) (Weaver et al., 1977). This favours the birth of a second generation of stars (*triggered* star formation) with a higher star formation efficiency (hereafter SFE) than the first one (*spontaneous* star formation). There are today several observational evidence of triggered star formation (Fich, 1986; Walter et al., 1998; Blum et al., 1999). For instance, within the violent interstellar medium of the nearby dwarf galaxy IC2574, Walter et al. (1998) have studied

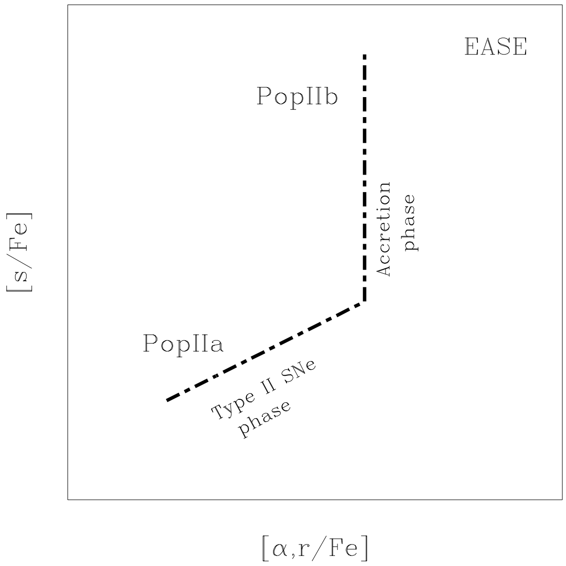

Fig. 2. EASE scenario (Jehin et al., 1999)

a supergiant HI shell obviously produced by the combined effects of stellar winds and supernova explosions. A major star formation event (equivalent to our first generation) has likely taken place at the center of this supershell and the most massive stars have released energy into the ISM. This one, swept by the blast waves associated with the first supernova explosions, accumulates in the form of an expanding shell surrounding a prominent HI hole. On the rim of the HI shell, Hα emissions reveal the existence of star forming regions (equivalent to our second generation). Actually, these regions of HI accumulated by the sweeping of the shell have reached densities high enough for a secondary star formation to start via gravitational fragmentation.

In our scenario, the second generation of stars formed in this dense and enriched shell makes up the proto-globular cluster. If the shell doesn't recontract, these stars form PopIIa and they appear somewhere on the slowly varying branch depending on the time at which the second generation formation has occurred. When all stars more massive than $9M_{\odot}$ have exploded as supernovae, the α and r element synthesis stops, leading to a typical value of [α/Fe]. Our scenario requires this typical value of [α/Fe] to be the maximum value observed in the *two-branches diagram* : the end of the supernova phase must correspond to the bottom of the vertical branch. If the proto-globular cluster survives the supernova phase, the shell of stars will recontract and form a globular cluster.

Phase 2

After the birth of the second generation, intermediate mass stars evolve until they reach the asymptotic giant branch where they enrich their envelope in s-process elements

through dredge-up phases during thermal pulses. These enriched envelopes are ejected into the ISM through stellar winds. Lower mass stars in the globular cluster can accrete this gas (Thoul et al., in preparation) : the s-process element enrichment occurs only in the external layers. With time, some of those stars can be ejected from the globular clusters through various dynamical processes, such as evaporation or disruption, and populate the galactic halo. These stars account for our PopIIb. Theoretically foreseen for a long time (see for example Applegate, 1985; Johnstone, 1992; Meylan and Heggie, 1997), these dynamical processes dislodging stars from globular clusters begin to rely upon observations. De Marchi et al. (1999) have observed the globular cluster NGC 6712 with the ESO-VLT and derived its mass function. Contrary to other globular clusters, NGC 6712 mass function shows a noticeable deficit in stars with masses below $0.75M_{\odot}$. Since this object, in its galactic orbit, has recently penetrated very deeply into the Galactic bulge, it has suffered tremendous gravitational shocks. This is an evidence that tidal forces can strip a cluster of a substantial portion of its lower mass stars, easier to eject than the heavier ones.
Our scenario requires that a significant fraction of the field stars now observed in the halo have been evaporated from globular clusters at an earlier epoch. Indeed, Johnston et al. (1999) claim that GC destruction processes are rather efficient : a significant fraction of the GC system could be destroyed within the next Hubble time. However, McLaughlin (1999) and Harris and Pudritz (1994) argue that these various destructive mechanisms are important only for *low* mass clusters. Therefore, these clusters cannot have contributed much to the total field star population because of their small size. As one can see, the origin of the field halo stars is still a much debated question.

In relation with the different steps proposed above to explain the observations, the scenario was labeled EASE which stands for *Evaporation/Accretion/Self-Enrichment* (Fig. 2).

3. Model description

3.1. The proto-globular cluster clouds

According to Fall and Rees (1985), PGCCs are cold ($T_c \simeq 10^4$K) and dense primordial gas clouds in pressure equilibrium with a hot ($T_h \simeq 2 \times 10^6$K) and diffused protogalactic medium. As already mentioned in section 1, the PGCCs can be maintained at a temperature of 10^4K only if some external heat sources were present at the protogalactic epoch. Fall and Rees (1988) and Murray and Lin (1993) have proposed that the UV flux resulting from the hot protogalactic background could be sufficient to offset the cooling below 10^4K in a gas with a metallicity less than [Fe/H]$\simeq -2$. As the PGCC is assumed to be made up of primordial gas (we deal with a *self*-enrichment model and not a *pre*-enrichment one), we will suppose it is indeed the case. Within the context of this preliminary model, the following assumptions are made :

- the PGCCs are thermally supported (no turbulence or magnetic field) and the PGCC primordial gas obeys the perfect gas law;
- a PGCC of mass M and radius R is an isothermal sphere in hydrostatic equilibrium, hence its density profile $\rho(r)$ scales as r^{-2} :

$$\rho(r) = \frac{1}{4\pi}\frac{M}{R}r^{-2}. \tag{1}$$

The requirement of pressure equilibrium at the interface between the cold and hot phases leads to

$$P(R) = \frac{kT}{\mu m_h} \times \rho(R) = P_h \tag{2}$$

where μ, T and P_h are respectively the mean molecular weight (μ=1.2), the temperature of the PGCC and the pressure of the hot protogalactic medium confining the PGCC. Equations (1) and (2) lead to a relation between the radius and the cubic root of the mass of the PGCC :

$$R_{100} = \chi M_6^{1/3}; \tag{3}$$

subscripts "100" and "6" mean that radius and mass are respectively in units of 100 parsecs and $10^6 M_{\odot}$. Upon the assumption of a temperature of 10^4K for the cold clouds, χ is defined by

$$\chi = \left(\frac{3.7 \times 10^{-12}}{P_h}\right)^{1/3} \tag{4}$$

where P_h is expressed in dyne.cm^{-2}. The mass of the PGCC is the mass of a pressure-truncated isothermal sphere of gas in hydrostatic equilibrium and is given by (McLaughlin and Pudritz 1996b) :

$$M = \sqrt{\frac{2}{\pi}}\left(\frac{kT}{\mu m_h}\right)^2 G^{-3/2} {P_h}^{-1/2}. \tag{5}$$

For a temperature of 10^4K, Eq. (5) becomes

$$M_6 = 1.1 \times 10^{-5} {P_h}^{-1/2}. \tag{6}$$

From equations (1), (3) and (6), the mass, the radius and the density profile of a PGCC bounded by a given pressure is completely determined. From this, we are able to find the expansion law for a supershell sweeping a PGCC. Contrary to Dopita and Smith (1986) who used the *current* gravitational potential of the Galaxy to evaluate χ, our determination is based on protogalactic conditions.

3.2. The formation of the first generation

It is well known that star formation can only occur in the coolest and densest regions of the ISM. We assume that the UV external heating provided by the hot protogalactic background is shielded by the bulk of the PGCC gas. Therefore, H_2 formation and thermal cooling are assumed to occur only near the center of the PGCC : the formation of the star first generation takes place in the PGCC central area, the densest and the coolest regions of the cloud. For the value of the SFE, i.e. the ratio between the mass of gas converted into stars and the total mass of gas, we refer to Lin and Murray (1992). Their computation shows that the early star formation in protogalaxies was highly inefficient, leading to a SFE not higher than one percent. The mass spectrum is described with the following parameters :

1. the slope of the initial mass function (IMF) α,
2. the lower m_{l1} and upper m_u mass limits of the spectrum,
3. the mass of the least massive supernova progenitor m_{l2},
4. the mass of the least massive supernova progenitor contributing to the PGCC self-enrichment m_{l3} ($> m_{l2}$).

The distinction between points 3 and 4 lies in the fact that the least massive supernova progenitors ($9 <$ M $< 12 M_{\odot}$) have very thin shells of heavy elements when they explode and contribute only very slightly to the chemical enrichment even if they are numerous. However, their dynamical impact on PGCC must be taken into account (stars with masses between m_{l2} and m_u end their live as supernovae, but only the ones with masses between m_{l3} and m_u participate to the chemical enrichment).

3.3. Supershell propagation

The model of Castor et al. (1975) primarily describes the evolution of a circumstellar shell driven by the wind of an early-type star. Their study can be extented to multiple supernova shells if the supernova progenitors (the first generation massive stars) are closely associated. In this case, all supernova shells will merge into a single supershell propagating from the center to the edge of the PGCC. Following the remarks of the previous section, we assume that this is indeed the case.

The blast waves associated with the first supernova explosions sweep the PGCC material in a thin, cold and dense shell of radius R_s and velocity $\dot{R}_s$. This shell surrounds a hot and low-density region, the bubble, whose pressure acts as a piston driving the shell expansion through the unperturbed ISM. The following equations settle the expansion law $R_s(t)$ of the shell during its propagation in a given PGCC (Castor et al., 1975; Brown et al., 1995) :

1. The supernova explosions add energy to the bubble at a rate $\dot{E}_o$ and the dominant energy loss of the bubble comes from work against the dense shell, hence the total energy of the bubble E_b is the solution from
$$\dot{E}_b = \dot{E}_o - 4\pi {R_s}^2 P_b \dot{R}_s. \tag{7}$$
2. The internal energy E_b and the pressure P_b of the bubble are related through
$$\frac{4\pi}{3} {R_s}^3 P_b = \frac{2}{3} E_b. \tag{8}$$
3. The motion of the supershell obeys Newton's second law
$$\frac{d}{dt}[M_s(t)\dot{R}_s(t)] = 4\pi {R_s}^2 (P_b - P_{ext}) - \frac{G{M_s}^2(t)}{2{R_s}^2(t)} \tag{9}$$
where $M_s(t)$ is the mass of the shell at time t and P_{ext} is the pressure in the unperturbed medium just outside the shell ($P_{ext} = P(R_s(t))$), which depends on the temperature of the isothermal cloud.
4. Knowing the density profile of the PGCC, we obtain the mass swept by the shell at time t
$$M_s(t) = \frac{M}{R} R_s(t) \tag{10}$$
where M and R are the mass and radius of the PGCC.

If, as assumed by McCray (1987), the energy injection rate $\dot{E}_o$ supplied by the supernova explosions is constant in time, then an analytical solution of the type $R_s(t) = v \times t$ describes the shell motion. In this expression, v is the constant speed of the shell during its progression through the PGCC. For an isothermal cloud of temperature T and mean molecular weight μ, relations (7-10) show that v depends on the PGCC mass and radius and on the supernova rate :
$$\left[3v^3 + 3\left(\frac{kT}{\mu m_H} + \frac{GM}{2R}\right) v\right] = 2\dot{E}_o \frac{R}{M}. \tag{11}$$
Since, the mass and the radius of the cloud are determined by Eq. (3),(4) and (6), the parameters of the problem are the pressure confining the PGCC and the supernova rate. Therefore, Eq. (11) successively becomes
$$[v_{10}^3 + (0.7 + 0.2\chi^{-1} M_6^{2/3}) v_{10}] = 3.3 \frac{NE_{51}}{\Delta t_6} \chi M_6^{-2/3}, \tag{12}$$
$$v_{10}^3 + 1.4 v_{10} = \frac{NE_{51}}{\Delta t_6}. \tag{13}$$
In Eq. (12) and (13), the bulk of the gas is assumed to be at a temperature of 10^4K, the mean molecular weight μ is set to 1.2, the expansion speed v_{10} is in units of 10km.s^{-1} (the sound speed value in a medium of this temperature), M_6 is the mass of the cloud in units of millions solar masses, N is the total number of SNeII, E_{51} is the energy provided by each Type II supernova explosion in units of 10^{51} ergs and Δt_6 is the supernova phase duration expressed in millions years. Equation (13) shows that the velocity of the shell depends on the number of SNeII and is independent on the hot protogalactic background pressure.

4. Level of self-enrichment

We have assumed that stars form in the central regions of a given PGCC. This first generation of stars is spontaneous, i.e. not triggered by any external event, a shock wave for instance. This results in a low SFE. After a few millions years, the massive stars ($9M_{\odot} < M < 60M_{\odot}$) end their lives as SNeII. The consequences are :

1. An enrichment of the primordial cloud. This is the *self-enrichment* phenomenon : the cloud has produced its own source of enrichment. As we will show below, this self-enrichment can explain the globular cluster metallicities.
2. A trigger of blast waves sweeping all the ISM in an expanding shell. The high density in the shell favours the birth of a second generation of stars with a higher SFE than for the first one.

4.1. Dynamical constraint

As the energy released by one SNII is typically 10^{51} ergs (E_{51}=1), the energy of a few supernova explosions and the gravitational binding energy of a PGCC are of the same order of magnitude. This is the major argument used against self-enrichment. Actually, it is often argued that successive supernovae will disrupt the proto-globular cluster cloud. To test whether this idea is right or not, we can compare the gravitational energy of the cloud to the kinetic energy of the expanding shell, supplied by the supernova explosions, when it reaches the edge of the cloud. Indeed, taking the following criterion for disruption :

$$\frac{1}{2}v^2 = \frac{GM}{R} \tag{14}$$

where $v = \dot{R}_s(t_e)$ and t_e is the time at which the shell reaches the edge of the cloud, i.e. the time at which the whole cloud has been swept-up in the shell, we have

$$t_e = \frac{R}{v}. \tag{15}$$

From equations (3), (12) and (14), we get

$$0.8\chi^{-3/2}M_6 + 0.6\chi^{-1/2}M_6^{1/3} + 0.2\chi^{-3/2}M_6 = 3.3\chi M_6^{-2/3}\frac{NE_{51}}{\Delta t_6}. \tag{16}$$

In this equation, N is the maximum number of SNeII a PGCC of mass M can sustain without being disrupted. The second and third terms in the left-hand side account for the decelerating effects produced by the external pressure and the shell gravity respectively. Again, using Eq. (4) and (6), we obtain

$$NE_{51} = 201 \tag{17}$$

where the duration of the SNII phase is set to 30 millions years ($\Delta t_6 = 30$). Therefore, a PGCC, here described by a pressure-truncated isothermal (T $\simeq 10^4$K) sphere of gas in hydrostatic equilibrium, can sustain *numerous* SNII explosions.

4.2. Chemical constraint

The first generation of stars is not triggered by any event (shock wave for instance) and therefore the SFE is likely to be be very low. The typical halo metallicity of [Fe/H]~ -1.6 must however be reached despite this low first generation SFE. We now show that this is indeed the case. We compute the relation between the mass of primordial gas and the number of first generation supernovae for two different cases. In the first case, we assume a given SFE (plain curve in Fig. 3), while in the second one, we impose the final metallicity (dashed curves in Fig. 3). In what follows, all the masses are in units of one solar mass.

The mass distribution of the first generation of stars obeys the following power-law IMF,

$$dN = km^{-\alpha}dm \tag{18}$$

where dN is the number of stars with masses between m and $m + dm$, α is the power-law index and k is a coefficient depending on the total mass of the first generation.

The PGCC (of total mass M) is made up of two components, one being the stars (total mass M^*), the other being the remaining gas, i.e. the gas not consumed to form the first generation stars (total mass M^{gas}). We can therefore write

$$M = M^* + M^{gas}. \tag{19}$$

The mass m_z of heavy elements ejected in the ISM by a supernova whose progenitor mass is m is approximatelly given by (Woosley and Weaver, 1995)

$$m_z = 0.3m - 3.5, \tag{20}$$

where $12 < m < 60$.

The total mass M^* of first generation stars, the number N of SNeII and the total mass M_z of heavy elements ejected by all supernovae are given by

$$M^* = \int_{m_{l1}}^{m_u} km^{-\alpha+1}\, dm, \tag{21}$$

$$N = \int_{m_{l2}}^{m_u} km^{-\alpha}\, dm, \tag{22}$$

$$M_z = \int_{m_{l3}}^{m_u} km^{-\alpha} m_z\, dm \tag{23}$$

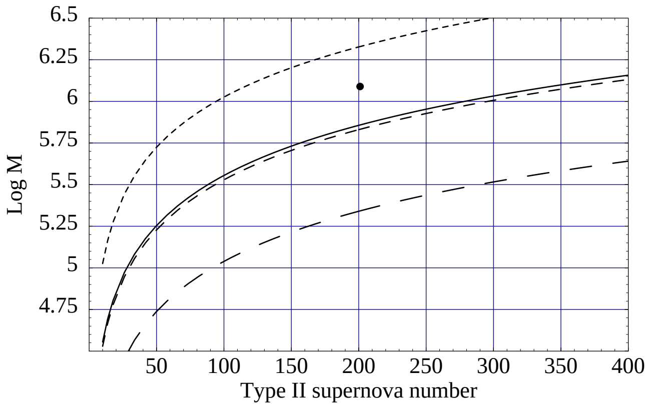

Fig. 3. Relations between the mass of the PGCC and the number of SNeII exploding in its central regions for a given SFE = 0.01 (plain curve), three self-enrichment levels (dashed curves), from up to bottom, [Fe/H]= $-2, -1.5, -1$. The point represents the dynamical constraint described in the text for a hot protogalactic background pressure of 8×10^{-11}dyne.cm^{-2}

where m_u is the upper mass limit, m_{l1} is the lower mass limit for the IMF, m_{l2} is the lowest star mass leading to a SNII and m_{l3} is the lowest star mass producing heavy elements.

If the mass M_z of heavy elements is mixed into a mass M^{gas} of primordial gas, the final metallicity [Fe/H] of the gas cloud is defined by

$$M_z = Z_{\odot} 10^{[\mathrm{Fe/H}]} M^{gas} \tag{24}$$

where $Z_{\odot}$ is the solar heavy element mass abundance.

Given either the SFE ($= M^*/M$) or the final metallicity [Fe/H], we can solve equations (18) to (24) to obtain the relationships between N and M in both cases. In Fig. 3, we have used $\alpha = 2.35$ (Salpeter 1955), $m_{l1} = 3(M_{\odot})$, $m_{l2} = 9(M_{\odot})$, $m_{l3} = 12(M_{\odot})$, $m_u = 60(M_{\odot})$, $M^*/M = 0.01$ and three different values for the final metallicity : [Fe/H]= $-2, -1.5$ and -1. We will justify these values for the IMF parameters in the next section. The point represents the dynamical constraint (17), namely the maximum number of SNeII a PGCC can sustain without disruption. The PGCC mass is set by the value of P_h (Eq. 6). The points located left/right correspond respectively to stable/unstable PGCCs. The last ones can't give rise to GCs as, following Eq. (14), they are disrupted. Similarly, the clouds with masses and number of SNeII above/under the plain curve (SFE=0.01) correspond to clouds with SFEs smaller/greater than one percent. The three dashed curves represent relations between the primordial gas mass and the number of SNeII at a given metallicity. From top to bottom, these metallicities are [Fe/H]=-1, -1.5, and -2. We deduce from Fig. 3 that we can achieve a metallicity [Fe/H]~ -1.5 with an SFE of one percent. Hence, *the mean metallicity of the galactic halo can be explained by the* *activity of a spontaneous first generation of stars, even with a low SFE.* Furthermore, the graphical comparison of the dynamical constraint with the set of curves corresponding to the three different metallicities shows that *the dynamical constraint is also compatible with the metallicities of some halo globular clusters* . For instance, under a hot background pressure of $8{\times}10^{-11}$ dyne.cm^{-2}, the mass of a PGCC is 1.2×10^6 M$_{\odot}$ and the metallicity that can be achieved through self-enrichment is -1.75. Table 1 illustrates the sensitivity of the model to the choice of P_h.

Table 1. Dependence of [Fe/H] on P_h

$P_h[dyne.cm^{-2}]$	$log_{10}M_c/M_{\odot}$	[Fe/H]
10^{-9}	5.5	-1.2
10^{-10}	6.0	-1.7
10^{-11}	6.5	-2.2

Our main conclusion is therefore that galactic halo globular cluster metallicities might be consistent with the process of self-enrichment, both from dynamical and chemical points of view.

It is clear that the metallicities presented in Tab. 1 are not compatible with the disk globular cluster metallicities. However, the metallicity distribution of the Milky Way GCs exhibits two distinct peaks, suggesting the existence of two subpopulations of GCs, a metal-poor one and a metal-rich one. The disk population might be a second generation of GCs formed out of gas where significant *pre*-enrichment had occured, due to the early formation of the galactic halo. For these clusters, there is no characteristic mass in the Fall and Rees sense : the temperature can decreased significantly below 10^4K as cooling is provided by the heavy elements. Therefore, others mecanisms must be invoked. For disk GC formation, see Burkert *et al.* (1992), Ashman and Zepf (1992).

5. Discussion

5.1. The IMF of the first generation

The first generation of stars forms out of a gas very poor, or even free, in heavy elements. We now examine the consequences for our model.

5.1.1. The shape of the IMF in a metal deficient medium

As already mentioned in section 3.2, we assume that the gas temperature can decrease significantly below 10^4K in the central regions of the PGCC only. We now focus on what might happen in this central region where star formation is expected.

According to Larson (1998), the Jeans scale can be identified with an intrinsic scale in the star formation process. It is defined as the minimum mass that a gas clump must have in order for gravity to dominate over thermal pressure (although the *thermal* Jeans mass is not universally accepted as relevant to the present-day formation of stars in turbulent and magnetized molecular clouds). It scales as

$$M_J \propto T^2 P^{-1/2} \tag{25}$$

where T is the temperature of the clump and P is the ambiant pressure in the star forming region (here the PGCC central area) surrounding the clump. There is therefore a strong dependence on the temperature. At T smaller than 10^4K, heavy elements and dust grains provide the most efficient cooling mechanism in present-day clouds while in primordial clouds the cooling process is likely to be governed by molecular hydrogen, the only available coolant in a zero metallicity medium. However, H_2 cannot cool the gas much below 100K while heavy elements can make the temperature as low as 10K. Therefore, we expect to have higher clump temperatures and therefore higher star formation mass scales in primordial gas than in current star forming regions. The IMF has in all likelihood evolved with metallicity and therefore with time, probably favouring higher masses in the early Universe. To take into account this time variability, Larson (1998) has proposed two alternative definitions for the IMF, where the slope is fixed (rather than variable as usually assumed in earlier analyses) and where the variable parameter is the mass scale m_1 :

$$\frac{dN}{d\log m} \propto m^{-1.35} exp(-m_1/m) \tag{26}$$

and

$$\frac{dN}{d\log m} \propto \left(1 + \frac{m}{m_1}\right)^{-1.35} . \tag{27}$$

These IMFs have a universal Salpeter form at large masses but depart from this power law below a characteristic mass that can vary (Fig. 4). Recent observational results suggest that the IMF has indeed a universal Salpeter slope at the upper end and that any variability should be confined to the lower end (Haywood 1994, Meyer et al. 1999). Contrary to the Salpeter IMF which raises monotically with decreasing stellar mass, the current observed IMF in the solar neighbourhood may be roughly flat at the lower end or even may peak at a mass around $0.25 M_\odot$ and decline into the brown dwarf regime. The uncertainty about the behaviour at the lower mass end comes from the fact that the IMF below $0.1 M_\odot$ remains very poorly known. Whatever the exact solution, a single power-law Salpeter IMF can be ruled out at masses lower than $1 M_\odot$, the IMF slope becoming clearly much smaller than the Salpeter value. The Larson IMFs (21) and (22) are in agreement with the observations since they reproduce the Salpeter's behaviour

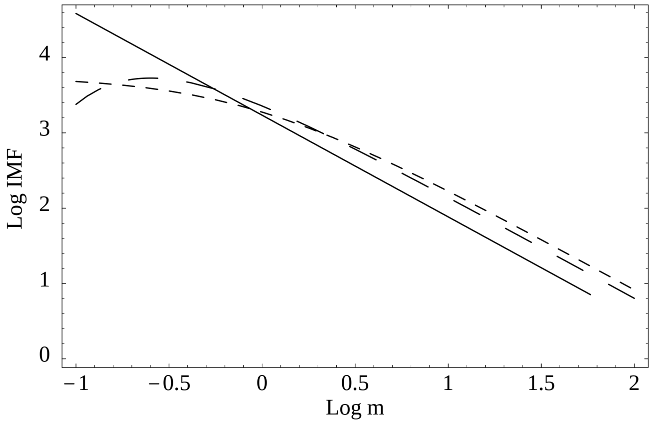

Fig. 4. Comparison of Salpeter IMF (plain curve) versus Larson modified IMFs (dashed curves). The results have been normalized in such a way that the mass integral is the same for the three IMFs

for large masses while they allow a large range of possibilities at the lower mass end depending on the value adopted for the mass scale m_1. The essential result is to alter the relative number of low-mass stars compared with the number of more massive ones. If the mass scale was higher at early times, relatively fewer low-mass stars would have been formed at these times.

Furthermore, Nakamura and Umemura (1999) have studied the cooling properties of molecular hydrogen. From this, they have estimated that, in a zero metallicity medium, the lowest mass star allowed to form is a $3M_{\odot}$ star. In other words, instead of any flattening or decline of the IMF, there is in this case a sharp cut off at the low mass end.

5.1.2. The star formation efficiency

The star formation efficiency is an important parameter, since the final mass fraction of heavy elements released in the primordial medium depends linearly on it. How stars are formed out of a gaseous cloud is still poorly known and it is not easy to estimate the value of the SFE. One of the most crucial step in the star formation process is the creation of molecular hydrogen (Lin and Murray 1992). H_2 cooling results in a rapid burst of star formation which continues until massive stars have formed in sufficient number to reheat the surrounding gas. The massive stars produce a UV background flux which destroys the molecular hydrogen by photodissociation and shuts down further star formation. Applying this principle of *self-regulated star formation by negative feed back* to a protogalactic cloud, Lin and Murray (1992) have calculated the UV flux necessary to destroy the molecular hydrogen and the required number of massive stars to produce this UV flux. Finally, the mass and the SFE of this first generation of stars in the protogalaxy

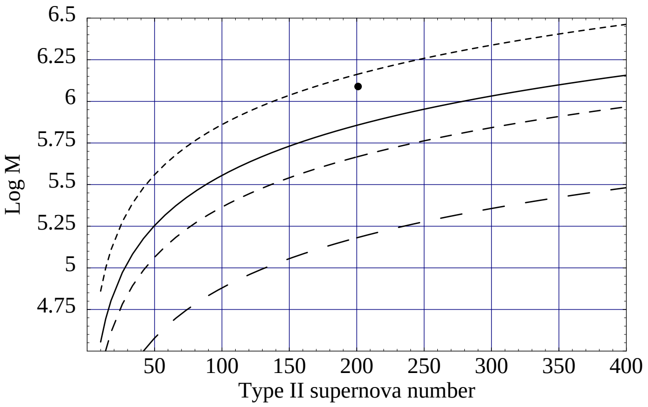

Fig. 5. Sensitivity to the mass spectrum upper limit. The curves shown here are similar to those in Fig. 3. Compared to these previous results, lower metallicity is reached if the upper mass limit of stars contributing to the enrichment of the ISM is set to 40M$_\odot$ instead of 60M$_\odot$

are estimated. They find a value of the order of one percent. Under the asumed IMF, an SFE of one per cent corresponds to a metallicity of -1.5 (see Fig. 3).

5.1.3. The upper limit of the mass spectrum

In the model we have adopted in section 4, the mass of heavy elements released by a star is proportional to its total mass (see Eq. (20)). However, above a critical mass m_{BH}, a star can form a black hole without ejecting the heavy elements it has processed. This critical mass is given by $m_{BH} = 50{\pm}10M_\odot$ (Tsujimoto et al., 1995). Moreover, Woosley and Weaver (1995) have shown that zero initial metallicity stars have a final structure markedly different from solar metallicity stars of the same mass. The former ones are more compact and larger amounts of matter fall back after ejection of the envelope in the SN explosion. In this case, more heavy elements are locked in the remnant left by the most massive stars. In order to evaluate the consequences for our model, we now define two different upper mass limits for the IMF. The mass of the most massive supernova contributing to the enrichment of the ISM is chosen to be $m_{u1} = 40M_\odot$. But the more massive stars will have a dynamical impact on the ISM and contribute to the trigger and the early expansion of the supershell, even though they will not contribute to the self-enrichment. All stars with masses between m_{l2} and m_{u2} end their lives as supernovae, but only the ones with masses between m_{l3} and m_{u1} contribute to the PGCC self-enrichment. We adopt $m_{u2} = 60M_\odot$ as the mass of the most massive supernova progenitor. This value is the same as in section 4.2 and therefore the plain curve in Fig. 3 (given SFE) is not modified. Keeping the same SFE, if we decrease m_{u1} from $60M_\odot$ to $40M_\odot$, there is a reduction of ~ 0.2 dex in the final metallicity (Fig. 5). An IMF with a Salpeter slope doesn't favour at all the highest mass stars and these stars are quite rare compared to the less massive supernovae. This explains why the final metallicity is not strongly dependent on the value of m_{u1}.

5.1.4. The lower limit of the mass spectrum

We have adopted the point of view of Nakamura and Umemura (1999) who assume that there is a sharp cutoff at the lower mass end of the IMF ($m_{l1} = 3M_{\odot}$). If we consider a pure Salpeter IMF, this parameter is very critical. Indeed, if we take $m_{l1} = 0.1M_{\odot}$ instead of 3, while keeping the SFE unchanged, the mass of heavy elements ejected by SNeII is decreased by a factor of four, leading to a decrease in metallicity of 0.6 dex. The Larson's modified IMFs provide less sensitive results.

5.1.5. The slope of the IMF

Following Larson (1998), we have used the Salpeter value. Changing the slope of the IMF will have the same consequences as changing the value of the lower mass cut off. If we decrease the slope, we will increase the ratio of high mass stars over low mass stars. The same result can be obtained by increasing the lower mass cut off of the mass spectrum.

5.2. Observational constraint : the RGB narrowness

With the exception of ω Cen, and perhaps M22, galactic globular clusters share the common property of a narrow red giant branch, indicative of chemical homogeneity within all stars of a given globular cluster. This observational property is also often used as an argument against self-enrichment. We now show that self-enrichment and a narrow RGB are in fact compatible.

5.2.1. The mass of the first generation stars

If we adopt the lower mass limit for the mass spectrum of initially metal-free stars proposed by Nakamura and Umemura (1999), we get rid of one of the major arguments against self-enrichment scenarios in globular clusters : the existence of two distinct generations of stars with clearly different metallicities. Indeed, if the first generation of stars is biased towards high mass stars as previously suggested, these stars are no more observed today and the current width of the RGB is not affected.

However, following Larson (1998), we could also allow low mass star formation during the first phase *but under a different mass-scale than today.* Using the IMF given by equation (26), we have computed the ratio between the currently observed numbers of low-mass

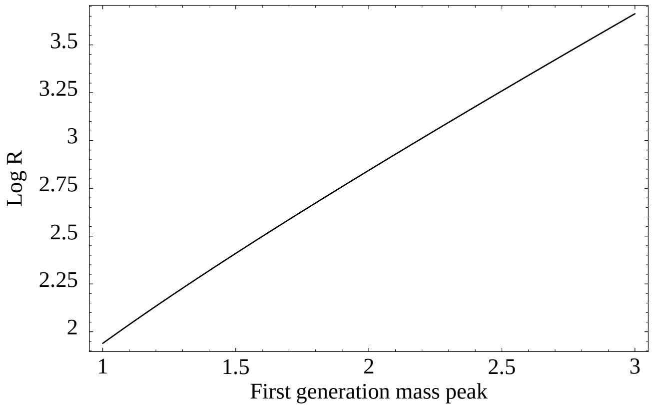

Fig. 6. Ratio R of the numbers of low mass stars in the two generations assuming that the second SFE is ten times higher than the first one. The second generation mass peak is $0.25M_{\odot}$ while the first generation mass peak is left as a parameter

($0.1M_{\odot} < M < 0.8M_{\odot}$) stars, which are produced in both generations. According to Brown et al. (1995), the second generation of stars will form a bound globular cluster if its SFE is at least 0.1. We therefore assume a value of 10 for the ratio SFE(2^{nd} generation)/SFE(1^{st} generation). The second generation mass scale m_1 (see Eq. (26)) has been fixed to $0.34M_{\odot}$ to match the solar neighborhood potential peak located at $m = 0.25M_{\odot}$ (see section 5.1.1). The mass peak of the first generation stars is left as a parameter and we allow it to vary between 1 and $3M_{\odot}$. The ratio R of the number of second generation low mass stars to the number of first generation low mass stars is shown in Fig. 6. For one metal-free star, the number of second generation stars lies between 100 and 4000 depending on the first generation mass peak. Thus, even if low mass stars were formed in the metal-free PGCC, their relative number observed today is so small that the existence of the first generation is not in contradiction with the RGB narrowness observed on globular cluster CMDs.

5.2.2. The time of formation of the second generation

Another controversial point about self-enrichment concerns the ability of the shell to mix homogeneously the heavy elements with the primordial gas. If the mixing is not efficient, inhomogeneities will be imprinted in the second generation stars formed in the shell and will show up as a broader red giant branch in CMDs, contrary to observations. Brown et al. (1991) have established that the accretion time by the blast wave propagating ahead of the shell is one to two orders of magnitude larger than the mixing time due to post-shock turbulence in the shell. In other words, the material swept by the shell is more quickly mixed than accreted and the post-shock turbulence insures supershell homogeneity. But even if the supershell is chemically homogeneous *at a given time*,

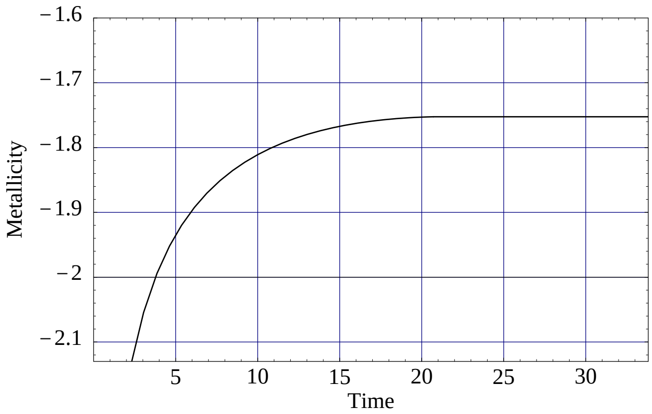

Fig. 7. Progressive enrichment due to Type II supernovae. Time is expressed in millions years

the chemical composition varies with time : metallicity is increasing as more and more supernova explosions occur at the center of the bubble. So, one can argue that the second generation will not be homogeneous : stars which are born early will be more metal-poor than stars which are born later, when self-enrichment has gone on. However, shell fragmentation into molecular clouds, in which second generation stars will form, cannot take place too early, at least not before the death of all first generation O stars. Indeed, these ones are the most important UV flux emitters and, as such, prevent the formation of molecular hydrogen.

It is very interesting to plot the increase of metallicity versus time when the shell has emerged in the hot protogalactic medium (all the cloud material has been swept in the shell whose mass is now a constant). For simplicity, we have assumed that the ejecta of one supernova mix with all the PGCC gas before the next supernova explosion. In Fig. 7, the parameter values are the same as in section 4 (same IMF, N=201, P_h=8 $\times$ 10^{-11} dyne.cm^{-2}) and the relation between the mass of a SNII progenitor and its lifetime on the Main Sequence is given by $\tau_{MS} \simeq 3 \times 10^7 yr[M_*/(10M_\odot)]^{-1.6}$ (Mc Cray, 1987). In this case, the shell reaches the edge of the cloud 2.3 millions years (explosion of the $35M_\odot$ supernovae) after the first explosion. We see in Fig. 7 that after a rapid increase in metallicity, as expected for a metal-free medium, the increase in metallicity slows down and saturates. After 9 millions years, when all stars more massive than $19M_\odot$ have exploded, the further metallicity increase is less than 0.1 dex, the upper limit of the RGB metallicity spread. Therefore, there is no conflict between a self-enrichment scenario and the RGB narrowness *if the second generation of stars is born after this time* . Even if supernova explosions still occur, the self-enrichment phase has ended. This point was already underlined by Brown et al. (1991) from a dynamical point of view.

6. Conclusions

We have investigated the possibility that globular clusters have undergone self-enrichment during their evolution. In our scenario, massive stars contribute actively to the chemical enrichment and to the gas dynamics in the early Universe. When a stellar system is formed, supernovae enrich the remaining gas in such a way that the next generation of stars is more metal-rich than the first one. In this paper, we assume the birth of a first generation of stars in the central areas of PGCCs. When the massive stars end their lives, the corresponding SNeII explosions trigger the expansion of a spherical shell of gas, where the PGCC primordial gas and the heavy elements ejected by supernovae get mixed. Because of the dynamical impact of supernova shock waves on the ISM, the gas is compressed into a dense shell and this high density favours the birth of a second generation of stars with a higher SFE. This scenario of triggered star formation is now confirmed by observational examples in the disk of our Galaxy and in irregular galaxies. The second generation stars formed in these compressed layers of gas are the ones we observed today in GCs. Others authors have proposed scenarios where these stars are also formed in triggered events, namely in gas layers compressed by shock waves, but the origin of the trigger is different. For instance, following Vietri and Pesce (1995) and Dinge (1997), the propagation of shock waves in the cloud could be respectively promoted by thermal instabilities inside the cloud or cloud-cloud collisions. Thus, in these scenarios, there is no first generation massive stars as shock wave sources : this is the major difference between our scenario and theirs.

It has long been thought that PGCCs were not able to sustain SNeII explosions because of the associated important energetic effects on the surrounding ISM. In this paper, we have shown that this idea may not be true. For this purpose, the criterion for disruption proposed by Dopita and Smith (1986) was used. Nevertheless, we have extended it to more general conditions. Owing to the shell motion description proposed by Castor et al. (1975), the spacing in time of the supernovae explosions was taken into account. Also, we have not considered a tidal-truncated cloud as Dopita and Smith did but a pressure-confined one, which is certainly more suitable to protogalactic conditions. With this model, we have computed the speed of propagation of the shell through the PGCC for a given supernova rate and a given external pressure. We have demonstrated that a PGCC can sustain many supernova explosions. Moreover, the dynamical upper limit on the number of SNeII is compatible with an enrichment of the primordial gas clouds to typical halo globular cluster metallicities. This conclusion is quite robust to changes in IMF parameters. Our result depends on the hot protogalactic pressure confining the PGCC and implies therefore a relationship between the metallicity and the radial location in the protogalaxy. We have also pointed out that a scenario which involves *two distinct* generations of stars is not in contradiction with the RGB narrowness noticed in CMDs of nearly all galactic globular clusters providing that the birth of the second generation of stars is not triggered before the $19M_{\odot}$ supernova explosions have occurred. In a forthcoming paper, the correlations expected from this self-enrichment model will be deduced and compared to the observational data of the galactic halo GCs.

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References

Applegate J.H., 1985, ApJ 301, 132

Ashman K.M., Zepf S.E., 1992, ApJ 384, 50

Blum R.D., Damineli A., Conti P.S., 1999, AJ, 117, 1392

Brown J.H., Burkert A., Truran J.W., 1991, ApJ 376, 115

Brown J.H., Burkert A., Truran J.W., 1995, ApJ 440, 666

Burkert A., Truran J.W., Hensler G., 1992, ApJ 391, 651

Castor J., McCray R., Weaver R., 1975, ApJ 200, L107

Cayrel R., 1986, A&A 168, 81

De Marchi G., Leibundgut B., Paresce F., Pumone L., 1999, A&A 343, L9

Dinge D., 1997, ApJ 479, 792

Dopita M.A., Smith G.H., 1986, ApJ 304, 283

Edvardsson B., Andersen J., Gustafsson B., et al., 1993, A&A 275, 101

Fall S.M., Rees M.J., 1985, ApJ 298, 18

Fall S.M., Rees M.J., 1988, J.E. Grindlay, A.G. Davis Philip, eds, IAU Symp. 126, Globular cluster systems in galaxies, p323

Falle S.A.E.G., 1981, MNRAS 195, 1011

Fich M., 1986, ApJ 303, 465

Harris W.E., Pudritz R.E., 1994, ApJ 429, 177

Haywood M., 1994, A&A 282, 444

Jehin E., Magain P., Neuforge C., Noels A., Thoul A.A., 1998, A&A 330, L33

Jehin E., Magain P., Neuforge C., Noels A., Parmentier G., Thoul A.A., 1999, A&A 341, 241

Johnston K.V., Sigurdsson S., Hernquist, L., 1999, MNRAS 302, 771

Johnstone D. 1992, AJ 105, 155

Kompaneets A.S., 1960, Soviet Phys. Doklady 5, 46

Larson B.L., 1993, Graeme H. Smith, Jean P. Brodie eds, ASP Conference Series, Volume 48, The globular cluster-galaxy connection, p675

Larson B.L., 1998, MNRAS 301, 569

Lin D.N.C., Murray S.D., 1992, ApJ 394, 523

McCray R., 1987, Roger, R.S., Landecker, T.L., eds, IAU Colloquium 101, Supernova Remnants and the Interstellar Medium, p447

McLaughlin D.E., Pudritz R.E., 1996a, ApJ 457, 578

McLaughlin D.E., Pudritz R.E., 1996b, ApJ 469, 194

McLaughlin D.E., 1999, AJ 117, 2398

Meyer R.M., Adams F.C., Hillenbrand, L.A., Carpenter, J.M., Larson, R.B., 1999, in press

Meylan G., Heggie D.C., 1997, A&AR 8, 1

Murray S.D., Lin D.N.C., 1993, Graeme H. Smith, Jean P. Brodie eds, ASP Conference Series, Volume 48, The globular cluster-galaxy connection, p738

Nakamura F., Umemura M., 1999, ApJ 515, 239

Nissen P.E., Høg E., Schuster W.J., 1997, Proc. of Hipparcos Venice 97 Symposium. ESA SP-402

Salpeter E.E., 1955, ApJ 121, 161

Tsujimoto T., Nomoto K., Yoshii Y., Hashimoto M., Yanagida S., Thielemann F.-K., 1995, MNRAS 277, 945

Vietri M., Pesce E., 1995,ApJ 442, 618

Walter F., Kerp J., Neb D., Brinks E., Klein U., 1998, ApJ, 502, L143

Weaver R., McCray, R., Castor, J., 1977, ApJ 218, 377

Woosley S.E., Weaver T.A., 1995, ApJSS 101, 181

Zhang M.; Ma E., 1993, Chin. Astron. Astrophys. 17/1, 43

Zhao G., Magain P., 1991, A&A 244, 425

Zinn R., 1985, ApJ 293, 424