OBSERVATIONAL CONSTRAINTS ON A SELF-ENRICHMENT MODEL IN GALACTIC HALO GLOBULAR CLUSTERS

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Abstract

We revisit the most often used argument against self-enrichment in globular clusters, namely the ability of a few number of supernovae to disrupt the proto-globular cluster cloud. We show that, within the context of the Fall and Rees theory, the progenitor cloud of a globular cluster is able to sustain a few hundreds of Type II supernovae without being disrupted. This large number of supernovae is able to produce the amount of metals currently observed in galactic halo globular clusters. The metallicity that can be reached through self-enrichment depends on the pressure exerted by the medium surrounding the progenitor cloud, and therefore on the cloud location in the Protogalaxy. This model provides therefore an explanation for the metallicity gradient observed throughout the Old Halo. A tentative comparison is also made between the mass-metallicity relationship expected by the model and the observational situation.

Key words: Stars: formation – globular clusters: general – Galaxy: evolution – supernovae: general

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. According to some scenarios, GC formation represents the high-mass tail of star cluster formation. Namely, the formation of bound stellar clusters occurs in the dense cores of much larger star-forming clouds whose mass is of the order of 10^8 $M_\odot$ (Harris & Pudritz 1994, McLaughlin & Pudritz 1996). Another type of scenario relies on a heating-cooling balance to preserve a given temperature and thus a characteristic Jeans mass at the protogalactic epoch. From this point of view, Fall & 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 diffuse protogalactic background. The temperature of the cold phase is assumed to be maintained at a value of 10^4K since the cooling rate drops sharply at this temperature in a metal-free medium. This assumption leads to a cloud mass of the order of 10^6 $M_\odot$. Since this is of the same order of magnitude as the GC mass (although a bit larger, but see below), Fall & Rees (1985) identify the cold clouds formed by the thermal instability with the progenitor clouds of GCs.

Within this context, the self-enrichment model was proposed by Cayrel (1986) and further developed by Brown et al. (1991) and Brown et al. (1995). The main advantage of this scenario is that it explains the formation of the cluster together with the origin of the cluster metal content. As already mentioned, the progenitor clouds are supposed to be metal-free and the formation process must therefore explain how the metals are provided within the clouds. That is why this model is called *self-enrichment*: a cloud is its own metal source.

Since the star formation timescale is shorter in the denser regions of the interstellar medium, a star formation event will occur first in the central regions of the cloud where the density is the highest. The massive stars of this *first generation* end their lives rather quickly, after a few million years, and explode as Type II supernovae (hereafter SNeII). The blast waves associated with the explosions trigger the formation and the expansion of a supershell in which all the cloud material is progressively swept. Also, the supershell gets chemically enriched with the metals released by the exploding massive stars. Since the supershell is a compressed layer of gas, it constitutes a dense medium where the formation of a *second generation* of stars is triggered. Under some 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 trigger the formation of the GC stars and provide the GC metals. Not all the supershell gas ends up in stars and the mass of the progenitor cloud must have been higher than the GC mass.

Supernova energetics has been a major criticism of the GC self-enrichment hypothesis. The energy released by a typical SN II and the binding energy of a still gaseous protocluster cloud are of the same order of magnitude. It might seem, therefore, that proto-globular clouds cannot survive a supernova explosion phase and are immediately disrupted (Meylan & Heggie 1997). There is however a difference between the kinetic energy of the ejecta and

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the kinetic energy effectively deposited within the cloud. Parmentier et al. (1999) have reconsidered this problem. In their model, the Proto-Globular Cluster Clouds (hereafter PGCCs) are assumed to be isothermal spheres in hydrostatic equilibrium and their density profile $\rho(r)$ scales therefore as r^{-2}. Knowing the density profile through which the supershell will propagate, the equations of the supershell motion (Castor et al. 1975) are solved, leading to the expression for the shell velocity. Then, the supershell kinetic energy, depending on the explosion rate, is compared to the PGCC binding energy. The comparison leads to an estimation of the SNII number that the PGCC can sustain without being disrupted.

2. Constraint on the SN number

Parmentier et al. (1999) have shown that, for a constant explosion rate, the velocity v of a supershell propagating throughout an isothermal sphere in hydrostatic equilibrium is constant in time and is given by

$$3v^3 + 3\left(\frac{kT}{\mu m_H} + \frac{GM}{2R}\right) v = 2\dot{E}_o \frac{R}{M} . \quad (1)$$

where M and R are the mass and the radius of the cloud, determined by P_h, the pressure of the hot protogalactic background confining the PGCC, k is the Boltzmann constant, T, the cloud temperature ($\simeq 10^4$K), μ, its mean molecular weight ($\simeq$1.2) and $\dot{E}_0$ the rate at which the SNII energy is supplied. With the hypothesis of pressure equilibrium between the hot and the cold media (Fall & Rees 1985) (cold clouds are pressure truncated), we get (see Parmentier et al. 1999 for details):

$$v_{10}^3 + 1.4 v_{10} = \frac{N E_{51}}{\Delta t_6} \quad (2)$$

where v_{10} is the shell velocity expressed in 10 km s^{-1}, N, the SNII number, Δt_6, the duration of the SNII phase expressed in millions years. E_{51} is the energy released by a SNII expressed in 10^{51} ergs. Typically, E_{51}=1.

The comparison of the PGCC binding energy to the kinetic energy of the supershell when this one reaches the edge of the cloud, namely when all the cloud has been swept, provides the disruption criterion:

$$\frac{1}{2}v^2 = \frac{GM}{R} . \quad (3)$$

From Eqs.2 and 3, we get the maximum number of SNeII that a PGCC can sustain without being disrupted:

$$N\, E_{51} = 200 ,$$

with $\Delta t_6 = 30$. One can observe that the SNII number is independent of P_h.

Since the self-enrichment process provides the GC metals, we wonder if the above dynamical constraint is compatible with galactic halo GC metallicities. This check is provided in Fig.1 where the dynamical constraint is plotted for different values of P_h, together with relations between the SNII number and the PGCC mass for 3 metallicities typical of the galactic halo. The results are also summarized in Table 1. Clearly, *GC halo metallicities can be reached through self-enrichment.*

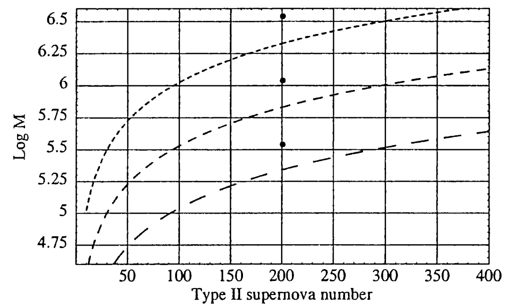

Figure 1. Relations between the mass of the PGCC and the number of SNeII exploding in its central regions for three self-enrichment levels (dashed curves), from up to bottom, [Fe/H] =−2, −1.5, −1. The points represent the dynamical constraint described in the text for 3 different hot protogalactic background pressures

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

P_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

3. The metallicity gradient

As one can observe in Table 1, the higher the external pressure is, the higher the metallicity will be. Indeed, since the dynamical constraint leads to a constant SNeII number, a constant amount of metals is released by the first generation massive stars. Since the PGCC mass decreases with increasing external pressure, 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* within the galactic halo.

At first sight, there is no agreement between this self-enrichment model and the observational data. The galactic halo exhibits no significant metallicity gradient (see Fig. 2; data are based on Harris 1996). However, according to Zinn (1993), the galactic halo may be composed of *two distinct subpopulations of GCs* : an Old Halo and a Younger Halo. This distinction is based on an analysis of the horizontal branch (hereafter HB) morphology. In some cases, two given clusters with the same metallicity have markedly different HB morphologies, e.g. M3 and M13, NGC362 and NGC288. M3 and NGC362 exhibit red HBs while M13 and NGC288 have blue HBs. This is the so-called "second parameter effect": a second parameter (at least), other than the metallicity, is required to

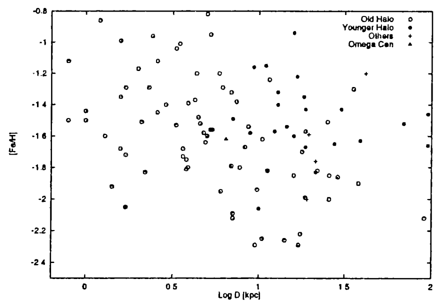

Figure 2. The whole galactic Halo exhibits no dependence of the metallicity on the galactocentric distance. It includes different subpopulations, for instance the Old Halo and the Younger Halo. The crosses represent the GCs related to Sagittarius A and Pyxis, an outer halo GC perhaps coming from the Magellanic Clouds. The triangle represents the most peculiar galactic GC, ω Cen (Data are based on Harris 1996).

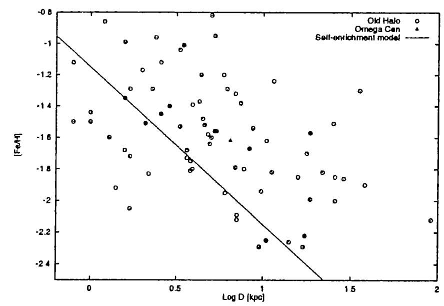

Figure 3. Comparison between the self-enrichment model gradient and the metallicity gradient observed throughout the Old Halo.

explain the HB morphology. Age has been proposed as a possible candidate (Zinn 1993) but this is still a much debated question. Whatever the nature of the second parameter might be, the hypothesis of the coexistence of two distinct halo GC populations has received some support from the recent work performed by Dinescu et al. (1999). They show that, on the average, the Old Halo and the Younger Halo exhibit some differences in their kinematics and their orbit shapes. The Younger Halo GCs have smaller rotation velocity, perhaps even retrograde, higher orbital energy, higher apogalactic distances and higher eccentricities. They are also located in the outer regions of the galactic halo, mostly beyond 10kpc. These observations provide some support to the concept of a dual formation of the galactic halo. Indeed, following Zinn (1993), the Old Halo GCs formed during the dissipative collapse of the protogalactic cloud while the more remote Younger Halo GCs formed inside satellite systems, e.g. dwarf galaxies, accreted and disrupted by the Milky Way. These Younger Halo GCs were therefore added to the *genuine* galactic GCs. Nature currently provides us with such an example of contamination. The dwarf galaxy Sagittarius A is currently disrupted by the galactic tidal field and its 4 GCs (M54, Arp2, Ter7 with halo metallicities and Ter8 with disk metallicity) are therefore incorporated in the galactic halo (Ibata et al. 1997). In Figs.2, the 4 crosses ("+: Others") represent the three Sag A GCs with halo metallicities and Pyxis, an outer halo GC which might be a detached cluster of the Magellanic Clouds (Irwin et al. 1995).

Since the self-enrichment model applies to GCs formed in our Galaxy, the Old Halo group only will be considered. This subdivision of galactic halo GCs is important from the point of view of the existence or not of a metallicity gradient: while the whole Halo and the Younger Halo do not exhibit any metallicity gradients, the Old Halo behaves differently (Fig.3). Is it in agreement with the gradient foreseen by the self-enrichment model ?

The relation linking the metallicity reached through self-enrichment and the pressure of the external medium confining the PGCC is given by (see Table 1):

$$[\mathrm{Fe/H}] = 3.3 + 0.5 \log P_{\mathrm{h}} \ . \qquad (4)$$

The corresponding metallicity gradient can be deduced if the profile of the hot protogalactic background pressure vs. the galactocentric distance is known. According to Harris & Pudritz (1994), the hot and diffuse phase of the Protogalaxy should be isothermal and in hydrostatic equilibrium with the dark matter potential, leading to a pressure profile that scales as D^{-2}, where D is the galactocentric distance. Murray & Lin (1992) reach the same conclusion and provide the following relation for the pressure profile:

$$P_{\mathrm{h}} = 1.25 \times 10^{-9} D_{\mathrm{kpc}}^{-2} \ . \qquad (5)$$

The metallicity gradient due to self-enrichment is therefore:

$$[\mathrm{Fe/H}] = -1.15 - \log \mathrm{D_{kpc}} \qquad (6)$$

In Fig.3, Eq. 6 and the observational data are compared. Theory and observations seem to be in good agreement despite a rather high dispersion in the observational data. Indeed, our model predicts a relation between the GC metallicities and the galactocentric distances of their *formation site*, from which they have, of course, drifted since their formation time.

4. The mass-metallicity relationship

Table 1 also suggests the existence of a relation between the mass M of a PGCC and the metallicity [Fe/H] reached at the end of the self-enrichment process. The higher the mass of the *proto-globular cluster cloud* is, the lower the metallicity will be :

$$[\mathrm{Fe/H}] = 4.35 - \log \mathrm{M} \ . \qquad (7)$$

However, such a tight correlation between both parameters is not expected for *globular clusters*. Indeed, there is

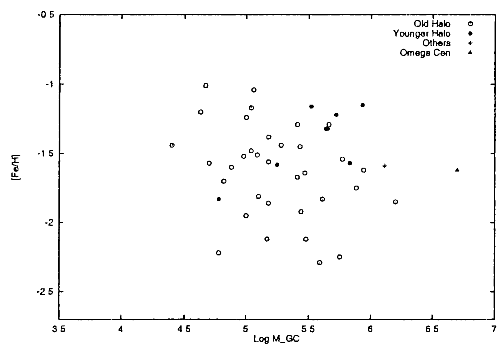

Figure 4. Plot of the metallicities [Fe/H] vs masses of galactic halo GCs: no trend emerges

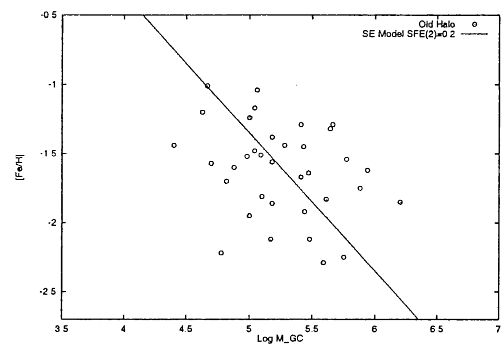

Figure 5. Same plot as in Fig. 4, but for the Old Halo GCs: a trend emerges in which the less massive clusters have higher metallicities. The straight line represents Eq.8 in which a value of 20% has been adopted for η

no reason why, in the supershell, the formation of the second generation stars would always occur with the same star formation efficiency (hereafter SFE). Introducing the SFE η of the second generation stars, Eq.7 becomes:

$$[Fe/H] = 4.35 - \log M_{GC} + \log \eta \ , \qquad (8)$$

where M_{GC} is the mass of the second generation of stars, namely of the newly formed GC. Instead of a correlation, we therefore expect a strip in the ($\log M_{GC}$, [Fe/H]) diagram, whose boundaries are set by an upper and a lower values of η (see Brown et al. 1995 for an estimation).

To see if there is an observational trend between the masses and the metallicities of GCs as predicted by the model, we have gathered as many GC masses as possible. We found 18 GC masses computed with a multi-mass model (see Parmentier et al., in preparation, and references therein). Because of the small size of this sample, we also computed masses with single-mass King models for 26 others GCs. We used the King formula (King 1966) reduced by Illingworth (1976) to

$$M_{GC} = 167 \mu r_c \sigma_0^2 \qquad (9)$$

where M_{GC} is the total mass of the cluster in solar masses, μ, a dimensionless parameter of the King model depending on the cluster concentration (see Table II, King 1966), r_c , the core radius in parsecs, and σ_0 , the central velocity dispersion in km s^{-1}. Core radius and concentration parameters are taken from Harris (1996). References for central velocity dispersions are given in Parmentier et al. (in preparation). The corresponding data are plotted in the ($\log M_{GC}$, [Fe/H]) plane in Fig.4 for all GCs for which masses have been computed, while they are restricted to Old Halo GCs in Fig.5. For the Old Halo GCs, there is indeed, on the average, *an increase of the metallicity with decreasing mass of GC*, as expected from the model.

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REFERENCES

Castor J., McCray R., Weaver R. 1975, ApJ 200, L107
Cayrel R. 1986, A&A 168, 81
Brown J.H. 1993, Graeme H. Smith, Jean P.Brodie, eds, ASP Conference Series, Volume 48, The globular clusters-galaxy connection, p 766
Brown J.H., Burkert A., Truran J.W. 1991, ApJ 376, 115
Brown J.H., Burkert A., Truran J.W. 1995, ApJ 440, 666
Dinescu, D.I., Girard, T.M., Van Altena, W.F. 1999, AJ 117, 1792
Fall S.M., Rees M.J. 1985, ApJ 298, 18
Harris W.E. 1996, AJ, 112, 1487
Harris W.E., Pudritz R.E. 1994, ApJ 429, 177
Ibata R.A., Wyse F.G.A., Gilmore G., Irwin M.J., Suntzeff N.B. 1997, AJ 113, 634
Illingworth G. 1976, ApJ 204, 73
Irwin M.J., Demers S., Kunkel W.E. 1995, ApJ 453, 21
King I.R. 1966 AJ 71, 64
Lee Y.W., Demarque, P., Zinn R. 1994, ApJ 423, 248
McLaughlin, D.E., Pudritz R.E. 1996, ApJ 457, 578
Meylan G. Heggie D.C. 1997, A&AR 8, 1
Murray S.D., Lin D.N.C. 1992, ApJ 400, 265
Parmentier G., Jehin E., Magain P., Neuforge C., Noels A., Thoul A.A. 1999, A&A 352, 138
Zinn R. 1993, Graeme H. Smith, Jean P.Brodie, eds, ASP Conference Series, Volume 48, The globular clusters-galaxy connection, p 38