Modes of Star Formation and the Origin of Field Populations
ASP Conference Series, Vol. 285, 2002
E. K. Grebel and W. Brandner, eds.

Evidence For a Self-Enrichment Process in Galactic Halo Globular Clusters

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Abstract. Based on accurate chemical abundance determinations in a sample of field halo stars (hereafter FHS), we define two FHS populations, related to two distinct stages of globular cluster (hereafter GC) chemical evolution, namely an early supernova phase and a subsequent accretion phase (EASE scenario). These stars were later dislodged from GCs through various dynamical processes. We have developed a model of GC self-enrichment, based on the ability of the GC gaseous progenitors to retain the ejecta of a first generation of Type II supernovae (hereafter SNeII). The model is able to explain the halo GC metallicities and the old halo metallicity gradient. It also implies a trend between the mass and the metallicity of GCs. Finally, we look at the conditions under which the expanding supershell, created by the SNII explosions, can undergo fragmentation (triggered star formation).

1. Introduction

Recent accurate chemical abundance determinations in mildly metal-poor field stars have revealed the existence of two stellar field subpopulations, namely population IIa and IIb (PopIIa and PopIIb; Jehin et al. 1999). To explain these two stellar populations, we have developed the EASE scenario (evaporation/accretion/ self-enrichment), which links the metal-poor field stars to the Galactic halo GCs. According to this scenario, the early chemical evolution of GCs includes two successive stages, a SNII phase and an accretion phase, during which low-mass stars accrete AGB winds. Each of these chemical stages leads to a different stellar population, PopIIa or PopIIb. At a later time, these stars are dislodged from GCs through various dynamical processes and join the field population. The observations and the EASE scenario are described in more detail in Jehin et al. (1999).

The EASE scenario therefore assumes that the supernova phase within the gaseous progenitors of Galactic GCs can indeed take place. Since the kinetic energy released by a SNII, typically $\sim 10^{51}$ ergs, is of the same order of magnitude than the GC binding energy, it might seem that a supernova phase cannot occur in a still gaseous GC without disrupting it (e.g., Meylan & Heggie 1997). However, this line of reasoning is in error, since the kinetic energy of the explosion differs from the kinetic energy deposited into the ISM. This problem is reconsidered in Parmentier et al. (1999).

2. The self-enrichment model

According to Fall & Rees (1985), the proto-Galaxy is a two-phase medium consisting of cold (T $\simeq 10^4$ K), dense clouds embedded in a hot (T $\simeq 10^6$ K) and diffuse protogalactic background. The cold clouds may be the gaseous progenitors of Galactic GCs. Parmentier et al. (1999) describe these cold clouds as isothermal spheres in hydrostatic equilibrium and pressure equilibrium with the surrounding hot protogalactic background. A first generation of zero-metal abundance stars is assumed to form in the central regions of each proto-globular cluster cloud (hereafter PGCC). The explosions of the corresponding SNeII trigger the expansion of a supershell into which all the cloud material is progressively swept. The shell gets chemically enriched by the SN ejecta: this is the *self-enrichment* process. Later on, a second generation of stars could form out of this enriched shell and recollapse, leading to GC formation (Brown et al. 1995).

In order to deal with one of the most often used argument against the hypothesis of self-enrichment in GCs (see Sect. 1), our model relies on the comparison between the gravitational energy of the PGCC and the kinetic energy of the supershell, the later depending on the number of SNeII. The corresponding amount of metals released into the ISM is then derived in order to check whether self-enrichment can explain Galactic halo GC metallicities. Final results are presented in Table 1 (see Parmentier et al. 1999 for details).

Table 1. PGCC masses and metallicities for different values of the pressure of the hot protogalactic background confining the PGCC

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

Clearly, halo GC metallicities can be attributed to self-enrichment and mostly depend on P_h, the pressure of the hot protogalactic background confining the PGCC. Furthermore, several predictions of our model can be compared to the observations. First, the higher the pressure of the surrounding hot gas, the higher the metallicity will be. Since the pressure is expected to be higher in the inner Galactic regions, a metallicity gradient should emerge if our model is correct. Secondly, the model predicts a mass-metallicity relationship for the *progenitor cloud.* A relic of this relation may still be present among halo GCs.

3. The metallicity gradient

The halo globular cluster system (hereafter GCS) presents no clear metallicity gradient. However, it seems likely that the halo GCS consists of clusters with more than one origin. According to Zinn (1993), the halo GCS includes two populations of GCs, the old halo (hereafter OH) group and the younger halo (hereafter YH) group. Both populations show differences such as in horizontal branch morphology, age, kinematics, and spatial distribution (see Parmentier et al. 2000 for a review). According to Zinn (1993), while the OH clusters are formed during the prompt collapse of the protogalactic cloud, the YH clusters are accreted later on by the Galaxy from dwarf galaxies. As a result, the YH group is not indicative of the formation of the Galactic halo and any comparison between the observations and the self-enrichment model should be limited to the OH sample. This separation is of great interest since, as expected from the self-enrichment model, the OH group exhibits a clear-cut metallicity gradient. A detailed analysis is presented in Parmentier et al. (2000). The conclusion is that, a pressure profile $P_h(D)$ scaling as $1/D^2$, where D is the Galactocentric distance, provides a metallicity gradient [Fe/H](D) in good agreement with the observational situation.

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, in the sense that the less massive clouds are the most metal-rich ones:

$$[\mathrm{Fe/H}] = 4.3 - \log M \; . \tag{1}$$

However, such a tight correlation is not expected for GCs. Indeed, there is no reason why, in the supershell, the formation of the second stellar generation would always take place with the same star formation efficiency (hereafter SFE). Figure 1 shows plots of [Fe/H] (Harris 1996, updated 1999) versus logM_{GC} for halo GCs (left hand panel: the 49 halo GCs from the Pryor & Meylan (1993) compilation; right hand panel: the presumed accreted component of the Galaxy has been removed). Since the mass M of a gaseous progenitor is an upper limit for the mass M_{GC} of the GC formed, Eq. (1) delimits a permitted area in the (logM_{GC}, [Fe/H]) plot: all the points should be located to the left of Eq. 1 (plain curve in the right hand panel in Fig. 1). It appears that it is mostly the case.

Introducing ε, the SFE of the second stellar generation, Eq.(1) becomes:

$$[\mathrm{Fe/H}] = 4.3 + \log\varepsilon - \log M_{GC} \; . \tag{2}$$

If ε did not vary too much from cloud to cloud, a relic of the PGCC mass-metallicity relation may still be present among halo GCs. Since the Pryor & Meylan compilation is an *homogeneous* set of GC masses, namely all the masses have been computed using the same type of multi-mass King models, it has the advantage to limit additional scatter in the observed (logM_{GC}, [Fe/H]) plot.

As for the metallicity gradient, a YH/OH separation is fruitful. Considering the OH group only, it separates into two different behaviors: at a metallicity lower than -1.8 dex, no clear trend emerges, while above this threshold, there is a pronounced increase of the metallicity with decreasing mass, as foreseen by the self-enrichment model. The linear Pearson correlation coefficient is -0.64 corresponding to a probability of correlation of 99.93%. In this metallicity range, a least-squares fit which takes into account errors in both coordinates (dashed curve) presents a shallower slope than the one of the model (plain curve). It is therefore suggested that ε decreases with decreasing PGCC mass.

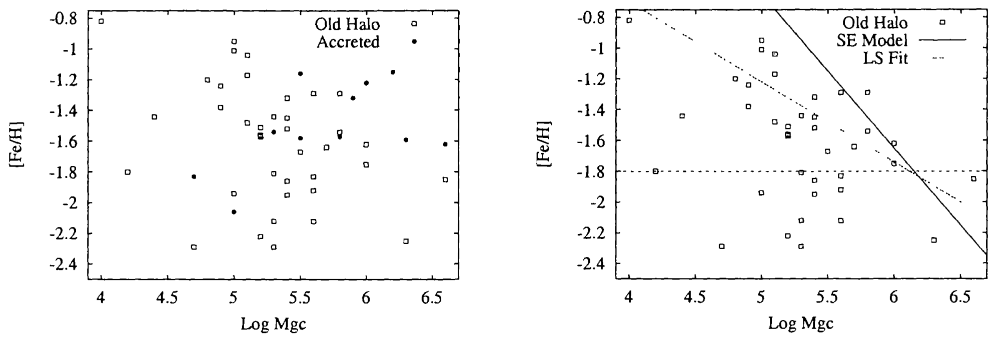

Figure 1. [Fe/H] vs log M_{GC}. Left panel: OH and YH subgroups (49 GCs). Right panel: OH subgroup (37 GCs). The correlation between the GC masses and their metallicities is particularly striking for [Fe/H]> -1.8. The corresponding least-squares fit (dashed curve) presents a shallower slope than the self-enrichment model (plain curve).

5. Is the supershell able to fragment ?

Up to now, we have *assumed* that a second generation of stars forms out of the supershell. We can ask whether the supershell is indeed able to become gravitationally unstable, namely to undergo transversal collapse in order to form some dense clumps of gas from which stars could form at a later time. To investigate this issue, we use the perturbed equations of continuity and momentum for transverse flows in the shell (Elmegreen 1994) [1]. We assume that the perturbed quantities vary exponentially with time and angular position in the shell. Therefore, we define an angular frequency ω and an angular wavenumber $\eta = 2\pi R_s/\lambda$ where R_s is the shell radius and λ is the wavelength of the gravitational perturbation. Then we get from the dispersion equation, ω=$\omega(\eta)$:

$$\omega = -\frac{3}{2}\frac{V_s}{R_s} + \sqrt{\frac{1}{4}\frac{{V_s}^2}{{R_s}^2} + 2\pi G\sigma_0\frac{\eta}{R_s} - {c_s}^2\frac{\eta^2}{{R_s}^2}} \tag{3}$$

where G is the gravitational constant, V_s is the shell velocity and c_s is the sound speed inside the shell. σ_0 is the unperturbed shell surface density, $M/(4\pi R_s^2)$. For the first growing mode (ω is maximum and $\frac{\mathrm{d}\omega}{\mathrm{d}\eta} = 0$), Eq. 3 becomes:

$$\omega_{fg} = -\frac{3}{2}\frac{V_s}{R_s} + \sqrt{\frac{1}{4}\frac{{V_s}^2}{{R_s}^2} + \frac{\pi^2\, G^2\, {\sigma_0}^2}{{c_s}^2}}\,. \tag{4}$$

Plots of $R_s(t)$ and $\omega_{fg}(t)$ are provided in Fig. 2 for different values of the external pressure P_h and for 200 SNeII, namely the number of SNeII given by the disruption criterion. The right hand panel suggests that whether the supershell

[1] In a first step, and since it is the longest phase of the SNII stage, we limit our study to the propagation of the supershell throughout the hot protogalactic background, namely all the PGCC has been swept into the supershell.

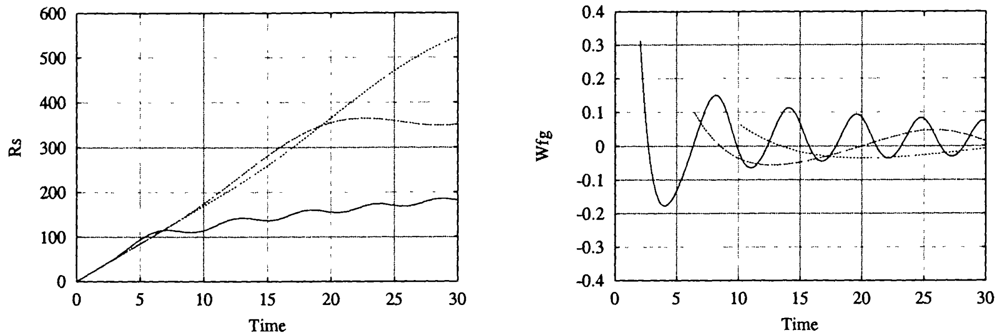

Figure 2. Left panel: radius of the supershell (in pc) vs time (in 10^6 years). Right panel: angular frequency of the first growing mode (in 10^{-6} years) vs time. Each ω_{fg} curve begins when the supershell crosses the PGCC boundary. In both panels, results are presented for 200 SneII and 3 values of P_h (10^{-10}, 10^{-11} and 4×10^{-12} dyne.cm^{-2}, plain, dash-dotted and dotted respectively)

can become gravitationally unstable ($\omega_{fg} > 0$) depends on P_h. At low pressure (e.g., $P_h = 4 \times 10^{-12}$ dyne cm^{-2}), and therefore at low-metallicity (see Table 1), the instability disappears. This might explain the end of the GC metallicity distribution function. However, this interesting conclusion must still be confirmed by more careful calculations since the gravitational instability must hold for a sufficiently long time to lead to a successful fragmentation.

Acknowledgments. This research was supported by contracts Pôle d'Attraction Interuniversitaire P4/05 (SSTC, Belgium) and FRFC F6/15-OL-F63 (FNRS, Belgium).

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Discussion

Mac Low: 1. What velocity dispersion was assumed in the shell? (That is, what determines the transverse velocities?) I ask because the shell running down the r^{-2} cloud density gradient will be Vishniak unstable (Mac Low & Norman 1992; Garcia-Segura & Mac Low 95).

2. When the shell begins to accelerate, as shown in your evolution at later times, it will become Rayleigh-Taylor unstable and fragment, releasing the interior pressure. How will this affect your results? (The same criticism applied to the work of Brown, Burkert, & Truran).

Parmentier: 1. The velocity dispersion during the propagation through the hot protogalactic background is assumed to be 1 km s^{-1}. The ability of the shell to undergo transversal collapse is indeed very sensitive to the value of c_s. If c_s is assumed to be 2km s^{-1}, the shell does not fragment during its early evolution due to a negative value of ω, the angular frequency of the perturbation. Later, the evolution of ω with time (assuming $c_s = 2$ km s^{-1}) looks the same as for $c_s = 1$ km s^{-1}. But at this time, the condition that the wavelength of the perturbation must be smaller than the shell dimension is no longer fulfilled, and fragmentation does not occur. Concerning the propagation through the PGGC, the expression for ω is different and has not been computed yet. Qualitatively, it scales as s/t. The sign of the accompanying factor should therefore be checked. Either the shell fragments (factor > 0) or it never does (factor < 0).

2. The first significant acceleration of the shell occurs after the shell has contracted for the first time, leading to a gravitational instability. Therefore, the Rayleigh-Taylor instability has no impact on the ability of the shell to form 2nd generation stars.

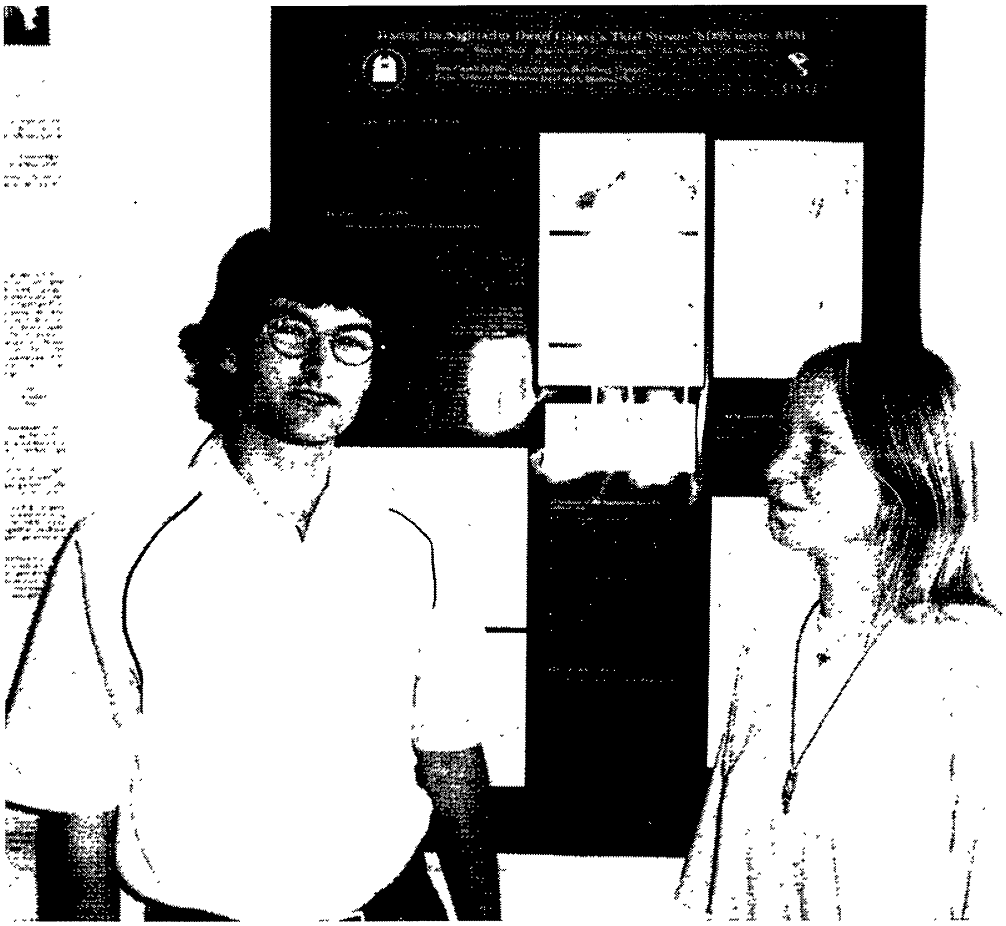
Elmegreen: What is the spread in metallicity in your models?

Parmentier: Any model of globular cluster formation should meet the observational constraint of chemical homogeneity. This is a twin-problem. First, the presence of low-mass stars of the first generation should lead to a widening of the red giant branch. But the number of these low-mass stars is expected to be smaller than the number of the low-mass stars of the second generation due to different star formation efficiencies. This difference is even more enhanced if the IMF of the first stellar generation (primordial medium) does not favor the formation of low-mass stars (top-heavy IMF).

The second point to check is the possibility that the formation of the second stellar generation occurs when (Fe/H) is still changing with time, leading to a spread in metallicity depending on the formation time of the stars. However, the increase of metallicity occurs during less than the first 10 million years of the evolution of the supershell (assuming that the ejecta are efficiently mixed into the supershell). This means that the chemical evolution is so quick that if the formation of the second generation stars does not occur before 8 or 9 million years after the first explosion, the spread in metallicity will be limited to not more than 0.1 dex, which is the observed value of metallicity spread in galactic GCs. Both points are addressed in Parmentier et al. (1999).

Part 6

Modes of Star Formation in the Galactic Disk



Bernd Lang and Andrea Stolte discussing an SDSS study of the Sagittarius dSph galaxy's tidal streams.