The EASE Scenario : Dynamical Study of the Supernova Phase

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Abstract. We revisit the most often encountered argument against self-enrichment in globular clusters, namely the ability of a few number of supernovae to disrupt the proto-globular cloud. We show that, within the context of the Fall and Rees theory, primordial proto-globular cluster clouds may sustain several hundreds of Type II supernovae. Furthermore, the corresponding self-enrichment level is in agreement with galactic halo globular cluster metallicities.

1 The EASE Scenario

Accurate abundance determinations among a sample of 21 mildly metal-poor stars ([Fe/H]$\simeq -1$) have revealed the existence of two sub-populations of halo and thick disk field stars, namely Population IIa (hereafter PopIIa) and Population IIb (hereafter PopIIb). They differ by the behaviour of the s-process element versus the α element abundances. The PopIIa shows a correlation between the relative abundances of light s-process elements, e.g. Y, and α elements, e.g. Ti, with a slope smaller than one. The PopIIb presents a constant and maximum [Ti/Fe] value and varying values of [Y/Fe] starting at the maximum value reached by the PopIIa. Stars more metal-poor than [Fe/H]$=-1$ also follow these correlations, while the disk stars do not. Therefore, low metallicity stars do follow a universal relation described by the *two-branches diagram*, schematically illustrated in Fig. 1.
In [1], we have suggested a scenario which closely relates the origin of these stars to early globular cluster (hereafter GC) evolution. Indeed, GCs might provide halo and thick disk field stars through various dynamical processes, such as dislocation or *evaporation*. According to this scenario, PopIIa and PopIIb are related to two different stages of the GC's chemical evolution. In the first phase, some Type II supernovae (hereafter SNeII), from a first generation of metal-free stars, enrich the medium in heavy elements, notably in α elements. This is the *self-enrichment* process. In the second phase, low-mass stars *accrete* material ejected by AGB stars, enriching their surface in s-process elements. Depending on the time at which stars are ejected from GCs, during the first phase or after the onset of the second one, they will define either PopIIa or PopIIb. This is the scenario EASE, *Evaporation/Accretion/Self-Enrichment*. Both EASE chemical stages, namely self-enrichment and accretion, are also illustrated in Fig. 1. The major goal of this work is to perform a dynamical study of the first phase, the SNII phase.

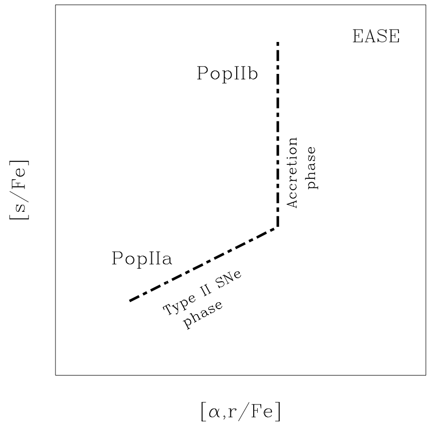

Fig. 1. EASE scenario

2 GC Formation Through Supershell Phenomenon

According to [2], the protogalaxy is a primordial two-phase medium, made up of cold and dense clouds embedded in a hot and diffused protogalactic background. A typical value for the temperature of the cold phase is 10^4 K, where the radiative cooling rate drops sharply in a metal-free medium. The cold clouds are supposed to be proto-globular cluster clouds (hereafter PGCCs), the progenitors of galactic GCs. We will describe them as isothermal spheres in hydrostatic equilibrium – their density profile $\varrho(r)$ scales therefore as r^{-2} – and assume that there is pressure equilibrium at the interface between the hot and the cold media. According to the Schmidt law, the denser the medium is, the quicker the stars will form. We therefore expect the formation of a first generation of stars in the PGCC central regions. After a few millions years, the massive stars of this first generation explode as SNeII. The blast waves associated with the explosions trigger the formation and the expansion of a supershell in which all the cloud material is swept. This supershell gets chemically enriched with the heavy elements released by the SNeII. Since the cloud has produced its own source of chemical enrichment, this phenomenon is called *self-enrichment*. In the supershell, in which all the cloud material gets compressed, the formation of a second generation of stars is triggered. This second generation forms a proto-globular cluster. In what follows, we restrict our analysis to *halo* GCs.
This scenario was proposed by [3] and further developed by [4] and [5]. However, even after these works, a recurrent argument has often been used against self-enrichment, namely the SN energetics. Since the binding energy of GCs today is of the same order of magnitude than the kinetic energy released by one SNII, several authors, e.g. [6], have concluded that a still gaseous proto-cluster could be immediately disrupted. Therefore, GCs could not be

self-enriched. However, it is important to distinguish the kinetic energy released by the exploding stars from the kinetic energy effectively deposited in the Interstellar Medium (hereafter ISM). We therefore suggest another criterion for disruption : the equality between the binding energy of the cloud and the kinetic energy of the shell when all the cloud has just been swept ([7]).

3 PGCC Model

The density profile of an isothermal sphere in hydrostatic equilibrium is

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

where M and R are its mass and its radius. The requirement of pressure equilibrium at the interface sets the value of M :

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

where k is the Boltzmann constant, T, the PGCC temperature, μ, its mean molecular weight (μ=1.2), G, the gravitational constant and P_{h}, the pressure value of the hot protogalactic background confining the PGCC.
In the same way, R and M are related by

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

where M_6 is the cloud mass expressed in units of $10^6\,\mathrm{M}_\odot$ and R_{100}, its radius expressed in units of 100 pc. The parameter χ is related to P_{h} (expressed in dyne.cm^{-2}) by

$$\chi = \left(\frac{3.7\times10^{-12}}{P_{\mathrm{h}}}\right)^{1/3} . \tag{4}$$

Equations (1)–(4) define the medium through which the supershell will propagate.

4 Supershell Velocity

The equations describing the supershell motion were defined by [8]. Under the reasonable assumption of a constant rate of the SNII explosions, the supershell velocity v is also constant in time and can be deduced from

$$3v^3 + 3\left(\frac{kT}{\mu m_H} + \frac{GM}{2R}\right)v = 2\dot{E}_o\frac{R}{M} , \tag{5}$$

where $\dot{E}_o$ is the rate at which the SNII energy is supplied. The second and third terms on the left-hand-side account for the decelerating effects respectively provided by the pressure external to the shell and by the shell gravity. With the different hypothesis about PGCCs, (5) can be reduced to

$$v_{10}^3 + 1.4 v_{10} = \frac{N E_{51}}{\Delta t_6} \tag{6}$$

where v_{10} is the shell velocity expressed in units of $10\,\mathrm{km.s^{-1}}$, N is the total number of SNeII and Δt_6, the duration of the SNII phase.

5 Disruption Criterion

We now introduce our criterion for disruption, namely the equality between the kinetic energy of the ISM, therefore of the supershell, and the binding energy of the PGCC :

$$\frac{1}{2} v^2 = \frac{GM}{R} \ . \tag{7}$$

Combining (2), (3), (4) and (6), and assuming a duration of the SNII phase of 30 millions years, we obtain an estimation of the maximum number of SNeII a PGCC can sustain without being disrupted, i.e.,

$$N E_{51} = 200 \ . \tag{8}$$

6 Self-Enrichment Level

Is the dynamical limit defined above in agreement with the metallicities observed in galactic halo GCs ? To answer this question, we define relations between the mass of a primordial gas cloud and the number of SNeII necessary to reach a given final metallicity. We assume that each massive star whose mass m is at least $12\,\mathrm{M}_\odot$ releases a mass of metals given by $0.3\mathrm{m}-3.5$ (in units of one solar mass) [9]. The upper limit of the spectrum is assumed to be $60\,\mathrm{M}_\odot$. The stars whose mass is between 9 and $12\,\mathrm{M}_\odot$ release unsignificant amounts of heavy elements. However, their dynamical impact on the cloud must be considered and they are therefore included in the total number N of SNeII. In Fig. 2, the relations between Log M and N for three given metallicities, typical of the galactic halo ([Fe/H]=−1, −1.5 and −2) are shown, as well as the dynamical constraint defined in Sect. 5 for a protogalactic background pressure of $2.5\times10^{-10}\,\mathrm{dyne.cm^{-2}}$. We see that a metallicity of −1.5 can be reached through self-enrichment. Therefore, the self-enrichment process may provide a clue to the metal amounts observed today in galactic halo GCs.
An interesting consequence of this model is the dependence on the value of P_h of the location of the dynamical constraint among the iso-metallicity curves (see (2) and (8)). The higher the pressure is, the higher the final metallicity will be. Therefore, this model provides an explanation to the metallicity gradient observed throughout the Old Halo [10].

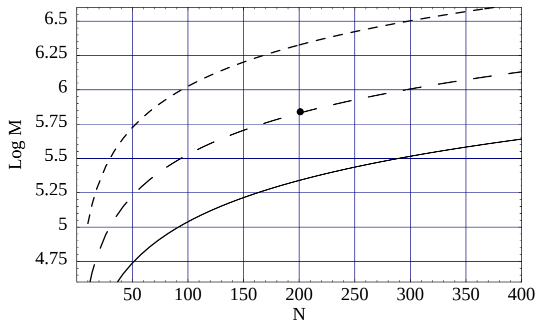

Fig. 2. Relations between the mass of the PGCC and the number of SNeII exploding in its central regions for three self-enrichment levels (*dashed curves*), from up to bottom, [Fe/H]= $-2, -1.5, -1$. The point represents the dynamical constraint described in the text for a hot protogalactic background pressure of 2.5×10^{-10} dyne.cm^{-2}

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