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On the Possibility of Self-Enrichment in Globular Clusters

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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 (GCs). The massive stars of a first generation, born in the central regions of proto-globular cluster clouds (PGCCs), explode as Type II supernovae (SNeII). The associated blast waves trigger the expansion of a supershell enriched by the heavy elements released by these massive stars. A second generation of stars, born in the shell, will lately form the GCs. We revisit the most often encountered argument against self-enrichment, namely the presumed ability of a small number of supernovae to disrupt PGCCs. With a model of the dynamics of the supershell and of its progressive chemical enrichment, it is shown that the minimal mass required to avoid disruption by several tens of SNeII is compatible with the masses usually assumed for PGCCs within the context of the Fall and Rees theory (1985). Furthermore, the corresponding self-enrichment level is in agreement with the halo GC metallicities.

1 Introduction

The Liege group currently develops a scenario about the chemical evolution of galactic globular clusters. This scenario aims to explain two subpopulations of halo and thick disk field stars by linking them to two distinct stages in the chemical evolution of GCs, a Type II supernova (SNII) phase and an accretion phase (Jehin *et al.*, Section II, Thoul *et al.*, this section). The scenario is therefore labelled EASE (Evaporation/Accretion/ Self-Enrichment). The purpose of this work is to investigate the possibility of the SNII phase from a dynamical point of view (Parmentier *et al.*, 1999).

2 GC Formation Through Supershell Phenomenon

We adopt the Fall and Rees (1985) theory as a description of the protogalaxy. Namely, dense and cold (T ~ 10^4K) clouds embedded in a diffuse and hot (T ~ 2×10^6K) protogalactic

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background are assumed to be the progenitors of galactic globular clusters. These PGCCs are assumed to be isothermal spheres in pressure equilibrium with the hot protogalactic background confining them. According to the Schmidt law, the denser the medium is, the quicker the stars will form. We therefore expect that the first stars that will form in the PGCCs will be centrally concentrated. After a few millions years, the massive stars of this first generation explode as SNeII. The blast waves associated with these explosions trigger the expansion of a supershell in which all the cloud material is swept up. Concurrently, the shell of gas is chemically enriched by the heavy elements released by the exploding massive stars. This is the *self-enrichment* process : the primordial cloud has produced its own source of chemical enrichment. The question then is whether this self-enrichment process is able to explain the metallicities currently observed in the galactic halo GCs.

In these compressed and enriched layers of gas, the formation of a second generation of stars is triggered. These stars can recollapse and form a GC. Such a formation scenario was successively proposed and developed by Cayrel (1986) and Brown, Burkert and Truran (1991, 1995). Despite these works, a recurrent argument was used against the possibillity of a self-enrichment phase in GCs. By comparing the kinetic energy of the ejecta of just one SNII and the binding energy of a still gaseous protoglobular cluster, several authors have concluded that this one could be immediatly disrupted. Therefore, from this point of view, GCs could not be self-enriched systems. However, it is important to point out that there is a difference between the kinetic energy of a SNII ejecta and the kinetic energy of the Interstellar Medium (ISM) : not all the kinetic energy of the ejecta is deposited as kinetic energy of the ISM. We therefore propose to revisit this argument. We suggest another criterion for disruption : the comparison between the binding energy of the cloud and the kinetic energy of the supershell when it emerges from the initial cloud (when all the cloud has been swept up in the supershell).

3 PGCC Description

To define this criterion, we need a description of the medium through which the supershell will propagate. As PGCCs are assumed to be isothermal spheres of gas, the density profile of a PGCC is given by

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

where M and R are the mass and the radius of the PGCC. Assuming that the PGCC primordial gas obeys the perfect gas law, the requirement of pressure equilibrium at the interface between the PGCC and the hot protogalactic background leads to the following relation between M_6 and R_{100}.

$$R_{100} = \left(\frac{3.7 \times 10^{-12}}{P_h}\right)^{1/3} M_6^{1/3} = \chi M_6^{1/3} \tag{2}$$

where P_h is the pressure of the hot protogalactic gas confining the PGCC, expressed in dyne.cm^{-2}, M_6, its mass in units of $10^6 M_\odot$ and R_{100}, its radius in units of 100 parsecs.

4 Supershell Motion

The equations defining the motion of the shell were early described by Castor, McCray and Weaver (1975) :

$$\dot{E}_b = \dot{E}_o - 4\pi {R_s}^2 P_b \dot{R}_s \tag{3}$$

$$\frac{4\pi}{3}{R_s}^3P_b = \frac{2}{3}E_b \tag{4}$$

$$\frac{d}{dt}[M_s(t)\dot{R}_s(t)] = 4\pi {R_s}^2(P_b - P_{ext}) - \frac{G{M_s}^2(t)}{2{R_s}^2(t)} \tag{5}$$

$$M_s(t) = \frac{M}{R}R_s(t) \tag{6}$$

In these equations, E_0 is the energy released by the SNeII, E_b and P_b are the energy and the pressure of the medium inside the shell and pushing it through the unperturbed medium of pressure P_{ext}, $R_s(t)$ and $M_s(t)$ are the radius and the mass of the shell at time t.
If we make the reasonable assumption that the SNII explosion rate is constant in time, it can be shown that the shell velocity through the PGCC is also constant in time ($\dot{R}_s(t) = v$). Using the hypothesis about PGCCs and appropriate units, we get Eq. (7) giving the velocity of the shell (in units of $10\mathrm{km.s}^{-1}$) for a given PGCC mass, a given hot protogalactic pressure and given number of SNeII. Δt_6 is the SN phase duration expressed in millions years.

$$[v_{10}^3 + (0.7 + 0.2\chi^{-1}M_6^{2/3})v_{10}] = 3.3\frac{NE_{51}}{\Delta t_6}\chi {M_6}^{-2/3}. \tag{7}$$

5 Constraint on PGCC Masses

We now introduce our criterion for disruption, the equality between the binding energy of the PGCC and the kinetic energy of the supershell, both expressed per mass unit :

$$\frac{1}{2}v^2 = \frac{GM}{R}. \tag{8}$$

In order to avoid disruption, the minimal mass of a PGCC, for a given protogalactic pressure, must obey the following relation obtained from Eqs. (2), (7) and (8)

$$0.8\chi^{-3/2}M_6 + 0.6\chi^{-1/2}M_6^{1/3} + 0.2\chi^{-3/2}M_6 = 3.3\chi {M_6}^{-2/3}\frac{NE_{51}}{\Delta t_6}. \tag{9}$$

Equation (9) is illustrated in Fig. (1) (dotted curve) with $P_h = 2.5 \times 10^{-10}\mathrm{dyne.cm}^{-2}$. Points located above the curve correspond to situations where the shell kinetic energy is less than the cloud binding energy. Such clouds are assumed not to be disrupted. The PGCC whose mass is the Bonner-Ebert critical mass ($M_{BE} = 1.2c^4G^{-1.5}P_h^{-0.5} = 10^6 M_\odot$ under the assumed conditions; c is the sound speed in the cloud material) can sustain more then 300 SNeII.

6 Self-Enrichment Level

The previous dynamical criterion defines a maximum number of SNeII for a given mass. As we deal with a process of self-enrichment, we now check whether this SNII number is able to enrich the primordial gas up to galactic halo metallicities. For a given mass of primordial gas and a given Initial Mass Function (IMF), here a Salpeter one, we compute the number of SNeII necessary to reach a given final metallicity. All supernovae whose mass m is between 12 and 60 $\mathrm{M}_\odot$ are assumed to release a mass $m_z = 0.3m - 3.5$ (in units of $\mathrm{M}_\odot$) of heavy elements. The *total* number of supernovae also take into account those whose mass is between 9 and 12

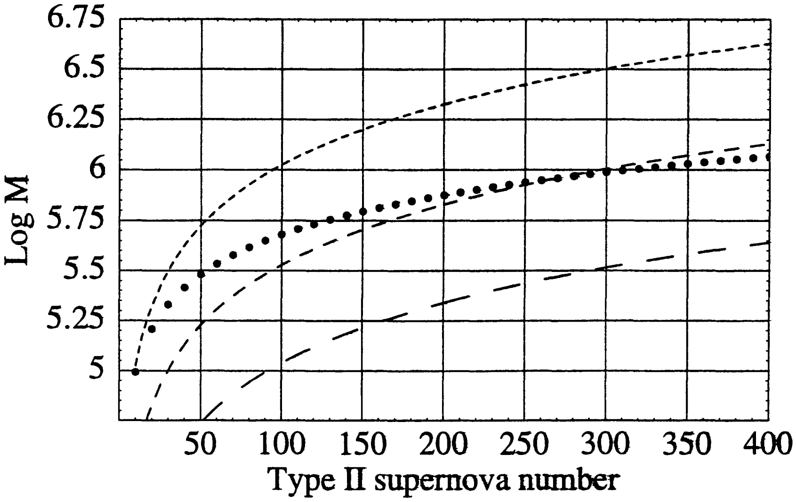

Figure 1: Relations between the mass of the PGCC and the number of SNeII exploding in its central regions for three self-enrichment levels (dashed curves), from up to bottom, [Fe/H]= $-2, -1.5, -1$, and the dynamical constraint described in the text (dotted curve)

$M_{\odot}$. Indeed, even if they release negligible amounts of heavy elements, their dynamical impact on the PGCC must be considered. From the comparison between these iso-metallicity curves ([Fe/H] $= -1, -1.5, -2$) with the dynamical constraint (Fig. 1), we conclude that PGCCs can be self-enriched up to metallicities typical of the galactic halo without necessarily being disrupted by the SNII explosions. More particularly, a PGCC whose mass is the Bonner-Ebert mass can be self-enriched up to a level of [Fe/H]=-1.5. Furthermore, as the position of the dynamical constraint among the iso-metallicity curves depends on the hot protogalactic background pressure, (see Eq. (9)), the self-enrichment level depends on the location of the PGCC in the protogalaxy. Therefore, this model is able to explain the *metallicity gradient* observed in the Old Halo (Zinn, 1992). (See also G. Parmentier *et al.*, Poster Section IV, this meeting)

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Discussion

C. Travaglio: Did you analyse, in the scenario that you presented, what's happened for example to oxygen ?

G. Parmentier: We tried to include in our analysis the yields published by Woosley and Weaver (1995). However, the type II SNe models are not precise enough to draw any conclusion, especially about our hypothesis related to Pop IIa origin.

G. Gilmore: Self-enrichment models should produce a correlation between the metallicity of a globular cluster and the mass of that cluster. Do your models do this in a way consistent with observations ?

G. Parmentier: This self-enrichment scenario indeed implies a correlation between the metallicity and the mass. However, it's quite hard to confirm from the observations : masses of globular clusters are not well determined (the mass-to-light ratios are rather dispersed) (see the review by G. Meylan), and the different papers don't always agree for the mass of a given globular cluster.