On star formation in primordial protoglobular clouds.

Paolo Padoan, Raul Jimenez, and Bernard Jones

1 Theoretical Astrophysics Center, Blegdamsvej 19, DK-2100 Copenhagen, Denmark
2 NORDITA, Blegdamsvej 17, DK-2100 Copenhagen, Denmark
3 Royal Observatory Edinburgh, Blackford Hill EH9 3HJ, Edinburgh, UK

29 July 2021

ABSTRACT

Using a new physical model for star formation (Padoan 1995) we have tested the possibility that globular clusters (GCs) are formed from primordial mass fluctuations, whose mass scale ($10^8 - 10^9 M_\odot$) is selected out of a CDM spectrum by the mechanism of non-equilibrium formation of $H_2$.

We show that such clouds are able to convert about 0.003 of their total mass into a bound system (GC) and about 0.02 into halo stars. The metal enriched gas is dispersed away from the GC by supernova explosions and forms the galactic disk.

These mass ratios between GCs, halo and disk depend on the predicted IMF which is a consequence of the universal statistics of fluid turbulence. They also depend on the ratio of baryonic over non-baryonic mass, $X_b$, and are comparable with the values observed in typical spiral galaxies for $X_b \approx 0.1 - 0.2$.

The computed mass and radius for a GC ($5 \times 10^5 M_\odot$ and 30 pc) are in good agreement with the average values in the Galaxy.

The model predicts an exponential cut off in the stellar IMF below 0.1 $M_\odot$ in GCs and 0.6 $M_\odot$ in the halo. The quite massive star formation in primordial clouds leads to a large number of supernovae and to a high blue luminosity during the first two Gyr of the life of every galaxy.

Key words: star: formation – globular clusters: formation – galaxy: formation
1 INTRODUCTION

Globular clusters are the fossil record of galaxy formation. They are among the oldest known objects in the Universe.

Since the first colour-magnitude diagrams (CMD) for GCs were obtained by Arp, Baum and Sandage (1952) in the early 50’s, GCs became the natural laboratory where the theory of stellar evolution was tested. On the other hand, the stellar evolution theory has allowed the determination of the age of GCs (e.g., Sandage 1962, Iben & Renzini 1984, Vandenberg et al. 1992, Jimenez et al. 1996), that is today considered as the best estimate for the age of the Universe.

Each galaxy contains hundreds of GCs, whose properties are surprisingly similar in the Universe (Harris and Racine 1979, Harris 1991), suggesting the presence of a common physical mechanism in the early stages of galaxy formation. The study of GCs should therefore provide important clues for the development of a theory for the origin of galaxies.

Sites of present day star formation do not form bound stellar systems as massive as GCs. Therefore modelling the formation of GCs could be a critical test for any theory of star formation.

It is known that stars are formed with an efficiency of a few percent in giant molecular clouds of the Galactic disk (Duerr, Imhoff & Lada 1982, Myers et al. 1986, Mooney and Solomon 1988), and bound open clusters with an efficiency ten times smaller (Larson 1986). Therefore it is not surprising if GCs contain only 0.1% of the luminous mass of the parent galaxy, since, from the point of view of the efficiency of present day star formation, they can only emerge from protoglobular clouds 1000 times more massive (as in Searle 1977, Searle & Zinn 1978, Harris & Pudritz 1994).

Nevertheless models of GCs formation have identified objects of just $10^6 \, M_\odot$ with protoglobular clouds. Such models place the GC formation period either before the galaxy is formed or during its formation. The first model for GCs as primordial objects was proposed by Peebles & Dicke 1968, and was later revised by Peebles (1984) and Rosenblatt, Faber & Blumenhal (1988). The secondary formation scenario, in which the mass of the protoglobular clouds are determined by the detailed mechanism of cooling in the protogalactic cloud, was first proposed by Fall & Rees (1985) and later improved by Kang et al. (1990), Ashman (1990), Brown, Burkert & Truran (1991), Brown, Burkert & Truran (1995), Vietri & Pesce (1995).
An alternative scenario has been proposed to explain the formation of some of the GCs in large shocks, e.g. in merging and interacting galaxies (Ashman & Zepf (1992), Kumai, Basu & Fujimoto (1993)).

In this paper we explore the possibility that GCs are formed in large clouds identified with primordial mass fluctuations in a cold dark matter (CDM) spectrum. The progenitors of GCs are clouds as massive as a few $10^8 M_\odot$ of baryons (Searle & Zinn 1978, Zinnecker et al. 1988 and Larson 1990 have suggested that GCs form in the core of very massive clouds). Such mass-scale is selected out of the standard CDM spectrum by the mechanism of non-equilibrium $H_2$ formation (see section 2) and, as mentioned above, it is required by the low efficiency of the process of star formation on large scales in order to form a bound stellar system.

The protoglobular cloud is efficiently cooled to approximately 100 K by $H_2$ collisional excitation. The cooling time is short enough that the gas can be considered isothermal. During the dissipative collapse (isothermal shocks radiate away most of the kinetic energy) of the baryonic gas (see section 2) star formation occurs until supernova explosions disperse away the gas (section 4).

We suggest that this star formation process in very massive primordial clouds can be responsible for the formation of the halo GCs (GCs with metallicity below 0.1 the solar value) and of a significant fraction of the halo stars. The dispersed metal-enriched gas is further processed in following star formation episodes.

The paper is organised in the following way. In section 2 we show how the mass-scale of protoglobular clouds is selected. Section 3 is a brief review of the statistical model of star formation (Padoan 1995) that is used in this work. Results are presented in sections 4 and 5. The last two sections of the paper contain the discussion and the conclusions.

2 THE MASS OF THE PROTOGLOBULAR CLOUD

If GCs have a primordial origin, then the mass of the typical protoglobular cloud should be of the order of $M_{\text{Galaxy}}/N_{\text{globulars}}$. On the other hand, it is observed that the specific frequency of GCs (Harris & Racine (1979)) in different spiral galaxies is approximately constant, which means that there must be a physical mechanism responsible for the value of the mass of the primordial protoglobular cloud. The value inferred from this argument is of a few $10^8 M_\odot$.

The rms fluctuation $\delta M/M$ in the mass inside a sphere of a given radius, which is an
integral over the power spectrum of density fluctuations, was determined by Peebles (1984) for a cold dark matter (CDM) scenario.

$\delta M/M$ is a shallow function of the mass scale without any particular feature. Nevertheless, a mass scale for the first baryonic fluctuations that collapse can be identified. Baryonic fluctuations of mass smaller than this will not collapse and fragment earlier.

The mass-scale is selected out of the CDM spectrum as a consequence of the mechanism of non-equilibrium formation of $H_2$. In fact the collapse and fragmentation of the gas in a gravitational potential dominated by collisionless dark matter particles requires energy dissipation, which becomes efficient as soon as a strong cooling mechanism is activated. We recognise such cooling mechanism in the $H_2$ collisional excitation.

The mass-scale arises because the formation of $H_2$ in the primordial gas (Peebles & Dicke 1968, Hirasawa 1969, Hirasawa, Aizu & Taketani 1969, Matsuda, Sato & Takeda 1969, Hutchins 1976, Silk 1977, Carlberg 1981, Palla, Salpeter & Stahler 1983, Lepp & Shull 1984) occurs during the non-equilibrium recombination (cooling time shorter than recombination time) of the $H_2$, that is in gas after strong ionising shocks (Lepp & Shull 1983, Dove & Mandy 1986, Shapiro & Kang 1987, Palla & Zinnecker 1988). The velocities necessary to produce such strong shocks are not present during the collapse of clouds of mass smaller than $10^8 \, M_\odot$.

Therefore efficient energy dissipation occurs only in primordial clouds of baryonic mass larger than $10^8 \, M_\odot$, and these clouds will be the first, in the CDM bottom-up hierarchy, to experience the fragmentation and collapse of their baryonic gas. The mass of the clouds given by this argument is comparable to the mass of protoglobular clouds as inferred above from the approximately constant specific frequency of GCs in galaxies.

We identify these primordial clouds of a few $10^8 \, M_\odot$ with protoglobular clouds.

3 A STATISTICAL MODEL FOR STAR FORMATION

A new statistical model of star formation has been recently discussed in a series of papers (Padoan 1995, Nordlund & Padoan 1996, Padoan, Jones, & Nordlund 1996, Padoan, Nordlund, & Jones 1996).

The model is relevant when the star forming gas is characterized by:

- random supersonic motions;
- cooling time shorter than dynamical time of the random motions.
Under these conditions a complex system of interacting isothermal shocks is present in the gas. Such flow creates a highly nonlinear density field, with density contrasts of a few order of magnitudes.

Since random motions are probably ubiquitous in sites of star formation, we suggest to describe the formation of protostars as the gravitational collapse of Jeans’ masses in a density distribution shaped by random supersonic motions. We therefore identify a protostar with one Jeans’ mass. The advantage of this description of star formation is that a statistical description of the density field arising from random motions in the gas can be given, and it does not depend on the detailed physics, but just on the rms Mach number of the flow.

In the following subsections we briefly present the results of recent numerical simulations of supersonic randomly forced flows, their observational counterpart, and the derivation of the protostar mass function (MF) based on the numerical (and observational) results.

### 3.1 Numerical experiments

Nordlund and Padoan (1996) and Padoan, Nordlund and Jones (1996) have recently discussed the importance of supersonic flows in shaping the density distribution in the cold interstellar medium (ISM).

They have run numerical simulations of isothermal flows randomly forced to high Mach numbers. A description of the code and the details of the experiments can be found in Nordlund & Padoan (1996).

Here we just mention that the experiments consist in solving the compressible MHD equations in a 3-D periodic mesh. A random force is applied in Fourier space to small wave numbers.

The random force produces a random flow, which is supersonic (rms Mach number up to 10). An isothermal equation of state is used, so that the flow soon develops a complex system of interacting shocks, with density contrasts of a few orders of magnitudes.

It is found that most of the mass concentrates in a small fraction of the total volume of the simulation, with a very intermittent distribution. The probability density function (pdf) of the density field is well approximated by a Log-Normal distribution:

\[
P(lnx)dx = \frac{1}{(2\pi\sigma^2)^{1/2}}e^{-\frac{1}{2}\left(\frac{lnx - \mu}{\sigma}\right)^2}dlnx
\]

where \(x\) is the relative number density:
\( x = n/\pi \) \hspace{1cm} (2)

and the standard deviation \( \sigma \) and the mean \( \ln x \) are functions of the rms Mach number of the flow, \( \mathcal{M} \):

\( \ln x = -\frac{\sigma^2}{2} \) \hspace{1cm} (3)

and

\[ \sigma^2 = \ln(1 + \frac{\mathcal{M}^2 - 1}{\beta}) \] \hspace{1cm} (4)

or, for the linear density:

\[ \sigma_{\text{linear}} = \beta(\mathcal{M}^2 - 1)^{0.5} \] \hspace{1cm} (5)

where \( \beta \approx 0.5 \). Therefore the standard deviation grows linearly with the rms Mach number of the flow.

It is also found that the power spectrum, \( P(k) \), of the density distribution is consistent with a power law:

\[ P(k) \sim k^{-2.6} \] \hspace{1cm} (6)

where \( k \) is the wavenumber.

An observational counterpart of these numerical results have been recently recognized by Padoan, Jones, & Nordlund (1996). They show that the infrared stellar extinction data presented by Lada et al. (1994) can be easily interpreted if the density distribution of the absorbing dark cloud is very intermittent. The observations are consistent with a Log-Normal distribution.

Padoan, Jones, & Nordlund have shown that the standard deviation and the power spectrum of the 3-D density distribution in the dark cloud can be constrained by the stellar extinction measurements. They find values of standard deviation and spectral index that are consistent with the numerical prediction.

In the following subsection, we show how to derive the MF of protostars, using the random density field predicted numerically and confirmed observationally in dark clouds.

### 3.2 The derivation of the stellar IMF

A simple way to derive the protostar MF is that of defining a protostar as one local Jeans’ mass, so that the protostar MF is simply a Jeans’ mass distribution. The Jeans’ mass
distribution is then just determined by the density distribution, because the gas is cooling rapidly and therefore the temperature is uniform.

In our scenario, random supersonic motions (cascading from larger scale) are present, and are responsible for shaping the density field. Strong density enhancements are due to the convergence of the flow, that is due to nonlinear hydrodynamical interactions, rather than to the local gravitational potential. We suggest therefore a description of star formation where random motions are first creating a complex and highly nonlinear density field (through isothermal shocks), and gravity then takes over, when each ‘local’ Jeans’ mass (defined with the local density) collapses into a protostar.

Let us start from equation (1), that is the statistic of the density, that means the fraction of the volume occupied by any given value of the density. If we multiply that function times the relative density \( x \), we get the fraction of the mass occupied by any given density:

\[
p(x)dx = xP(x)dx
\]

\[\tag{7}\]

Now let us imagine to filter the density field with a filter of radius \( R_i \), that corresponds to the mass scale \( M_i \). We can sample the density distribution using this filter, and repeat the operation for different filters. For any scale \( M_i \) we get a distribution of density \( P_i(M_i, x) \).

We know, from the numerical simulations and from the observations mentioned above, that the Log-Normal distribution is a good model of the statistic of the density field. Therefore we have a Log-Normal distribution, \( p_i(M_i, x) \), for every mass scale \( M_i \), each with its own value for the standard deviation, \( \sigma_i \), and for the mean, \( \ln x_i = -\sigma_i^2/2 \).

The fraction of the total mass in collapsing structures of scale \( M_i \) is the integral of the distribution \( p(M_i, x) \) along relative densities \( x > x_{J,i} \):

\[
\int_{x_{J,i}}^\infty p(M_i, x)dx
\]

where \( x_{J,i} \) is the Jeans’ density for the Mass \( M_i \). But of course the structure of radius \( R_i \) can contain many local Jeans’ masses, especially if it is very dense, and therefore can fragment into smaller objects. For this reason we must repeat the same argument for a mass scale \( M_{i+1} < M_i \), and subtract the collapsing mass fraction in objects of radius \( R_{i+1} \), from the previously calculated collapsing mass in objects of radius \( R_i \):

\[
\int_{x_{J,i}}^\infty p(M_i, x)dx - \int_{x_{J,i+1}}^\infty p(M_{i+1}, x)dx
\]

The situation is illustrated in fig.1a, where two filter masses, \( M_1 \) and \( M_2 \) are shown.
Now, one should go to the limits \( M_1 \rightarrow M_2 \) and \( x_{J,1} \rightarrow x_{J,2} \), and take the derivative along mass of an integral along density,

\[
\frac{\partial}{\partial M} \int_{x_{J,M}} p(M, x) dx
\]

where also the lower extreme of integration is subject to the derivative.

The whole procedure of extracting the protostar MF from the density distribution can be made much easier, by assuming the distribution \( p(M_i, x) \) to be the same for any \( M_i \). This is in fact a good approximation, because we know from the numerical experiments and from the observations mentioned above, that the power spectrum is \( P(k) \propto k^n \), where the spectral index \( n = -2.6 \pm 0.5 \).

The standard deviation \( \sigma_i \) is the mass variance that defines the power spectrum:

\[
\sigma^2(R) = \frac{1}{2\pi^2} \int_{k}^{\infty} k^2 P(k) dk
\]

from which we can write:

\[
\sigma(M) \propto M^{-\frac{n+3}{6}}
\]

where \( n \) is the spectral index. For a spectral index \( n = -2.6 \) we obtain \( \sigma(M) \propto M^{-0.07} \). Since the exponent is so small, the distribution of density is approximately the same for any filter:

\[
p(M_i, x) dx = p(x) dx
\]

In other words we can say that the power spectrum is steep enough that the density field is almost self-similar, when looked through different filters.

Fig.1b is the simplified version of fig.1a. Now the problem of deriving the mass function has become trivial, since the subtraction of the collapsing structures of scale \( M_{i+1} \), from the probability of collapse at the scale \( M_i \), is simply the derivative, along masses, of an integral along density, whose integrand do not depend on mass:

\[
\frac{\partial}{\partial M} \int_{x_{J,M}} p(x) dx
\]

The solution is just the value of the integrand at \( x_J \), times \( dx_J / dM \). So we can see that the MF for the protstars, \( p(M) \), is just given by the transformation of the density distribution into a Jeans’ mass distribution:

\[
p(M) dM = p(x) dx
\]

where \( M \) is the Jeans’ mass for the relative density \( x \), or vice versa.

The Jeans’ mass can be written as:
\[ M = M_J = 1M_\odot B x^{-1/2} \]  

(11)

where:

\[
B = 4 \left( \frac{T}{10K} \right)^{3/2} \left( \frac{n}{1000 cm^{-3}} \right)^{-1/2}
\]

(12)

is the average Jeans’ mass, that is the Jeans’ mass for the average density \( x = 1 \).

Here we use the simplest definition of Jeans’ mass: without turbulent pressure or rotation, because the gas has just been shocked and is dissipating its kinetic energy in a short time; without magnetic pressure, because we will discuss the role of the magnetic field in such random flows in subsequent papers (our numerical experiments are in fact solving the MHD equations).

Using equations (1), (7), (10), (11), and (12) we get the protostar MF:

\[
p(M)dM = \frac{2B^2}{(2\pi\sigma^2)^{0.5}} M^{-3} \exp \left[ -\frac{1}{2} \left( \frac{2lnM - A}{\sigma} \right)^2 \right] dM
\]

(13)

where \( M \) is in solar masses, and:

\[
A = 2\ln B - \ln x
\]

(14)

One can also express the MF in average Jeans’ mass, instead of in solar masses:

\[
\frac{p(M)}{B}d(M) = \frac{2}{(2\pi\sigma^2)^{0.5}} \left( \frac{M}{B} \right)^{-3} \exp \left[ -\frac{1}{2} \left( \frac{2ln(M/B) - |lnx|}{\sigma} \right)^2 \right] d(M/B)
\]

A log-log plot of the protostar MF is shown in fig.2. One can recognize a long tail at large masses and an exponential cutoff at the smallest masses, inherited from the Log-Normal distribution of density. This shape is a good result, because most models for the origin of the stellar IMF are not able to reproduce the cutoff at the smallest masses, which should be present in any reasonable IMF.

The dependence of the MF on the physical parameters of the star forming gas (average temperature, density and velocity dispersion) is discussed in Padoan, Nordlund, & Jones (1996), where a comparison with the observations is also presented.

If the MF is expressed per linear mass interval (eg number of stars rather than mass fraction), its maximum occurs at the mass:

\[
M_{max} \approx 0.07M_\odot \left( \frac{n}{1000 cm^{-3}} \right)^{-1/2} \left( \frac{T}{10K} \right)^{9/4} \left( \frac{\sigma_v}{2.5 km/s} \right)^{-3/2}
\]

(15)

(Padoan, Nordlund, Jones 1996). This is the typical stellar mass.

The result of the present derivation of the MF is that basically all the gas turns into stars (of different masses), after the density distribution [1] is established. This is a process...
that takes about one dynamical time of the random motions on the large scale. Therefore the star formation efficiency, defined as the star formation rate per unit mass, is just the inverse of the dynamical time of the random motions.

4 THE FORMATION OF THE STELLAR CLUSTER

Since the typical mass of the protoglobular cloud is determined by the condition that $H_2$ can be formed during the collapse, the cooling time in the gas ($10^5$ yr at a temperature of 200-300 K) is much shorter than the free-fall time (a few $10^8$ yr). Therefore the cloud is collapsing at a constant temperature of about 100 K. The collapse will be a turbulent flow with a complex system of strong isothermal shocks, where high density fluctuations are produced and protostars are born according to the model of turbulent fragmentation. The high Reynolds number in the gas flows, the initial density inhomogeneities expected from the CDM scenario and the shear motions due to the tidal field are together responsible for the turbulence during the collapse. Moreover, any initial turbulence will be exponentially amplified during the collapse (Rotman 1991, Jacquin, Cambon & Blin 1993).

In order to apply the statistical model of star formation, we use an average density profile that is a power law, $\rho(r) \propto r^{-3/2}$, where $r$ is the distance from the center. This is the density profile of the inner portion of a free falling isothermal sphere (Larson 1969, 1973, Shu 1977).

Using this density profile, the temperature of 100 K and the turbulent velocity dispersion equal to half of the free fall velocity, we can calculate the IMF and the star formation rate as a function of the distance from the center of the cloud during the collapse of this.

Since the density is higher in the center than in the outer parts, the star formation rate is increasing towards the center. This means that at some point during the collapse a bound stellar system could be formed around the center, while the remaining gas would be dispersed by supernova explosions. The main aim of this work is to test if that bound system looks like a GC and if the scenario is consistent with observational constraints related to the formation of the Galaxy.

4.1 Formation of a bound system

The star formation process continues as long as the collapse is taking place, that is until the energy injected in the system by supernova explosions becomes larger than the gravitational energy of the cloud. When this happens, if at all, a bound stellar system will be left only if
On star formation in primordial protoglobular clouds.

Figure 1. Total gravitational energy of the protoglobular cloud (continuous line) and kinetic energy input from supernovae (dashed line). The energy is in arbitrary units and the density in cm$^{-3}$. The cloud is destroyed by the supernovae when it has reached an average density of about 1 cm$^{-3}$.

The total mass of the stars is comparable or larger than the mass of the dispersed gas (Lada, Margulis & Dearborn 1984).

We compute the star formation rate and the IMF during the collapse - i.e., at different densities. At any given density, we compare the total gravitational energy of the cloud with the kinetic energy injected into the gas motions by explosions of stars more massive than 8 $M_{\odot}$. Every supernova is supposed to liberate an energy of $10^{51}$ ergs that is turned into kinetic energy of the surrounding gas with an efficiency of 1% (examples of efficiency estimates are given in Spitzer 1978, Brown, Burkert & Truran 1995).

In Fig. 1 we show that the total energy of the gaseous cloud becomes positive when the average cloud density is equal to 1.0 cm$^{-3}$. At this density the collapse is stopped and the gas is dispersed away from the stars, marking the end of the star formation process.

In order to check if a bound stellar system is formed at all, we compute the star formation efficiency (mass star/total mass) at different distances from the center of the cloud; the bound stellar system is formed wherever the efficiency is close to 100%, in Fig. 2 the star formation
efficiency is plotted versus a radial coordinate (mass fraction). The efficiency falls below 50% at a mass fraction of about 0.004, that corresponds to a radius of 50 pc.

Therefore our star formation model applied to a primordial cloud of $2.5 \times 10^8 \, M_\odot$ predicts the formation of a bound stellar system with a mass of $5 \times 10^5 \, M_\odot$ and a radius of 30 pc.

The integration of the function plotted in Fig. 2 shows that approximately 0.002 of the total mass of the cloud has turned into a bound stellar system and 0.02 into stars located outside the bound system, that will evaporate and eventually form the halo of the Galaxy (without including the bulge component).

4.2 Initial mass function

The IMF and its typical mass are given by the formula 1 and 6 (section 3). The IMF for GCs is plotted in Fig 3 (dashed line). The IMF has a single maximum, an exponential cut off for smaller masses and a long intermittent tail for larger masses. In the figure we plot with the continuous line the exponent ($x(m)$) of the power law IMF that approximates the predicted IMF. The slope for masses below $1 \, M_\odot$ is always smaller than the Salpeter, $x = 1.35$, and the maximum is located at $0.1 \, M_\odot$. The slope becomes equal to the Salpeter one around $2 \, M_\odot$ (not shown in Fig 3).

Therefore our model predicts that deep luminosity functions observed in GCs should be characterised by a cut off at luminosities corresponding to masses of about $0.1 \, M_\odot$ preceded by a progressive flattening of the distribution.

5 GLOBULAR CLUSTERS AND THE GALAXY

The picture of GC formation proposed in the present work implies the following scenario for galaxy formation:

- The protogalaxy is an ensemble of a few hundred primordial clouds of about $10^8 \, M_\odot$ that are in self collapse.
- One GC is formed inside the nucleus of each cloud.
- The remaining part of the cloud forms the halo stars that evaporate from the cloud.
- The cloud gas that is expelled out by the supernova explosions falls dissipatively into a disk system.

As we mentioned above, most of the stars formed outside the bound system are evaporated from the cloud. The total mass in this stellar component is about 10 times larger than
Figure 2. Star formation efficiency (mass in stars over initial gaseous mass) versus mass fraction (0.0 in the center, 1.0 at the largest radius) at the end of the star formation process. The dashed line shows the fraction of left over gas at any position from the center.

the mass of the GC. Moreover, the total mass of the dispersed gas is around 500 times the mass of the GC.

Therefore our model predicts reasonable mass ratios between GCs and galaxy masses (Harris & Racine 1979) and between GCs and the stars in the external halo (Woltjer 1975, Bahcall & Soneira 1982, Harris & Racine 1979). Moreover, it also predicts the IMF for halo stars and the initial metallicity of the galactic disk. The halo IMF is shown in Fig 4.

The most probable mass of halo stars is 6 times more massive than the one in GCs. This is due to the fact that halo stars are formed at a lower density in more external regions of the primordial cloud compared to GC stars. So we predict that deep stellar counts of halo stars will show a cut off in the IMF below 0.6 \( M_\odot \).

The gas that falls into the disk system is previously metal-enriched by the star formation in the protoglobular clouds. Therefore we expect to find virtually no disk stars with metallicity lower than \([O/H]= -1\).
6 DISCUSSION

In this paper we have presented a model for the formation of the halo population of stars (bulge excluded) and GCs (metallicity below 0.1 the solar value). The visible mass of such population in the Galaxy is a few percent of the total Galactic mass for the halo stars and a few per thousands for the GCs. These mass ratios are reproduced by the present model for reasonable values of the non-baryonic mass of the Universe.

Searle & Zinn (1978) and Zinn (1985) have proved the existence of two distinct populations in the system of Galactic GCs. The two populations differ in metallicity and kinematic properties. The halo GCs show no metallicity gradient outside 8 Kpc from the Galactic center while the disk GCs show a metallicity gradient and a minimum metallicity [Fe/H]=-1.

Several authors have proposed distinct mechanisms for the origin of the two GCs populations (Searle & Zinn 1978, Zinn 1985, Rosenblatt, Faber & Blumenthal 1988, van den Bergh 1993), while no attempt has been made here to model the formation of the disk GCs.

The halo GCs have been explained as the result of the star formation process in primordial mass fluctuations in a CDM spectrum; halo stars are also formed in this way. The typical mass of primordial protoglobular clouds is explained by assuming that the onset of H$_2$ cooling is essential for the collapse and fragmentation of the baryonic gas in gravitational potentials dominated by collisionless dark matter. In fact, it is the short cooling time in the gas that makes the shocks isothermal, so that purely baryonic strong density enhancement can be achieved, and the collapse and fragmentation of the baryonic gas can proceed.

We have found that the ratio of baryonic to non-baryonic mass, $X_b$, plays an important role in the formation of the combined system of halo GCs and halo stars. If $X_b \sim 0.1$ too massive GCs are formed, in contradiction with the observations. On the other hand the formation of the estimated value of the mass of halo stars requires $X_b \sim 0.2$.

We can conclude that the primordial origin of halo GCs and halo stars in the CDM scenario is feasible only if $X_b = 0.1 - 0.2$, that is the density parameter $\Omega = 0.2 - 0.5$, if the baryonic density parameter $\Omega_b = 0.05$ (Kolb & Turner 1990).

6.1 The initial mass function

Our statistical model of star formation is based on a fragmentation mechanism controlled by the statistics of fluid turbulence. The universal character of the statistical properties
On star formation in primordial protoglobular clouds.

Figure 3. IMF in GCs. The dashed line shows the IMF in arbitrary units; the maximum is at 0.1 $m_{\odot}$. The continuous line gives the exponent ($x(m)$) of the power law IMF that approximates that segment of the predicted IMF. The slope for masses below 1 $M_{\odot}$ is always smaller than the Salpeter $x=1.35$.

of turbulence generate a functional form of the stellar IMF which does not depend on environmental physical parameters, even though the typical stellar mass does.

The GCs IMF has its low mass cutoff at 0.1 $M_{\odot}$. The slope of the IMF ($x=1$ at 0.8 $M_{\odot}$) is smaller than the Salpeter one ($x=1.35$), and becomes comparable with it at about 2 $M_{\odot}$.

There have been attempts to determine the IMF in GCs. Fahlman et al. (1989), Richer et al. (1991) and Piotto & Ortolani (1991) find very steep IMFs. Nevertheless these determinations are affected by several uncertainties, the most important being the unknown mass-luminosity relation. Moreover the measured IMFs span only a very limited range in masses (0.2-0.7 $M_{\odot}$) in the best case, making any extrapolation for other masses very uncertain.

Recent HST observations find a cutoff in the IMF at about 0.1 $M_{\odot}$, in good agreement with our prediction.

Models of GCs evaporation and core collapse (Hut & Djorgovskv (1992)) are consistent
with observations if the average stellar mass is assumed to be 0.3 M\(_\odot\), consistent with our model.

The expected non-baryonic dark matter inside the GC is only a small fraction of the GC mass because the high velocity (about 100 km/s) of the dark matter particles prevents them from falling into the baryonic central density condensation. As for the baryonic dark matter, our IMF contains a negligible number of brown dwarfs and jupiterian objects. Therefore the total dark matter content of GCs is expected to be small, in agreement with the observations.

The predicted stellar masses in the halo are 6 times larger than in the GCs. This is due to the smaller average density of the gas where halo stars are formed (the maximum in the halo IMF corresponds to a density of 250 cm\(^{-3}\) and in the GC of 10000 cm\(^{-3}\)). The halo stellar population is also more massive than the solar neighbourhood one, suggesting that the star formation process in the early protogalaxy is characterised by the presence of a large number of supernovae, compared with the subsequent star formation in the disk. Therefore the contribution to brown dwarfs and jupiters from the halo stars is also negligible.

The halo IMF implies that in the evolution of every galaxy there will be a high blue luminosity during the first 2 Gyr. This event should be included in models of galactic luminosity evolution to be used for the interpretation of deep galaxy counts.

We predict a halo IMF that is less steep than the Salpeter’s one below 2 M\(_\odot\). Richer & Fahlman (1992) observed low mass stars down to 0.14 M\(_\odot\) in the halo and suggested that the slope of the IMF is instead steeper than the Salpeter’s one. On the other hand, more recent HST observations by Bahcall et al. 1994 of high latitude fields found fewer faint red stars.

### 6.2 Metallicity

Halo GCs in large galaxies show a dispersion in metallicity that is much larger than the internal one (Harris and Racine (1979)); this fact is sometimes used as an argument against the primordial origin of GCs, because it is believed that self-enrichment in the protoglobular cloud should lead to a heterogeneous metallicity distribution inside the GC.

Nevertheless in our picture the stars responsible for the enrichment are formed during the dissipative collapse of the baryonic cloud, which takes a few 10\(^8\) years. This time scale is long enough to allow for efficient mixing if only the central region of the cloud, where the GC will be formed, is considered. The bulk of GC stars are formed in a period of only
On star formation in primordial protoglobular clouds.

10^7 years (because of the stellar feedback that destroys the cloud), when the central average density has become large enough, and therefore such stars cannot be responsible for any further self-enrichment. On the other hand the efficient mixing for the whole cloud requires a longer time than for the nucleus, so that some stars will be formed outside the GC with very low metallicity. In fact the metallicity distribution of halo stars is known to extend to practically zero metallicity (Beers & Sommer-Larsen (1995)).

Only a few supernovae are required to enrich the primordial cloud and achieve the value for the metallicity observed in halo GCs. The small number of supernovae easily explains the range in metallicity observed in halo GCs, as due to statistical fluctuations in the number of supernovae events, before the final star formation burst.

Our scenario for GC formation is not only consistent with metallicity determinations in GCs but also with the observed lower limit for the disk metallicity: there are virtually no disk stars found with metallicity lower than [O/H] = −1.0 (van den Bergh 1962, Schmidt 1963, Beers & Sommer-Larsen 1995). We calculate the oxygen yield from the star formation...
in the protoglobular cloud, and find that the metallicity of the gas, that is dispersed from
the cloud and falls into the disk, is about $[\text{O/H}]=-1.0$. So we do not expect any disk star
to be formed with metallicity lower than this value, in agreement with the observations.

The observed abundances of oxygen over iron in halo stars (Matteucci & Greggio 1986,
Wheeler, Sneden & Truran 1989, McWilliam & Rich 1994), and the fact that the median
halo stars metallicity (Norris 1986) is about the same as the median metallicity in GCs,
suggest that halo stars and GCs belong to the same star formation process as stated in our
model.

7 CONCLUSIONS

The main conclusions of this paper are the following:

• GCs can be formed out of the nucleus of a primordial cloud of a few $10^8 \, M_\odot$ of baryons.

• The mechanism of $H_2$ formation selects this typical mass scale out of a CDM spectrum.

• Most halo stars in the galaxy (bulge excluded) can be formed together with the (halo)
GCs in the same clouds; the halo and the GCs masses are sensitive to the ratio of baryonic
over non baryonic matter, $X_b$, in the cloud.

• A ratio $0.1 < X_b < 0.5$ produces realistic values for the mass of GCs; if $X_b < 0.1$ too
large GCs are formed.

• A ratio $X_b < 0.2$ is needed in order to originate most of the halo stars in the protoglob-
ular clouds during the formation of GCs.

• The gas that is blown away from the disrupted protoglobular cloud by supernova ex-
plosions is used in the following star formation episodes; therefore the initial disk metallicity
(minimum stellar metallicity in the disk) is $[\text{O/Fe}]=-1$.

• The IMF in GCs has a cut off below $0.1 \, M_\odot$ while the halo IMF has the cut off below
$0.6 \, M_\odot$.

• During the first 2 Gyr of its life each galaxy has higher blue luminosity than normal
disks. This is due to the fact that star formation (halo stars) in the protoglobular cloud
produces a significant number of massive stars, which also means an epoch of large number
of supernova explosions.

We have shown that this scenario is consistent with several observations.

The star formation rate and the stellar IMF are essential ingredients of the model. In
order to predict them we have used a new physical model of star formation. In this model
the functional form of the IMF is shown to be universal because it is based on the statistics of turbulence which are universal properties of flows.

Future work should concentrate in the attempt of simulating the collapse of CDM primordial protoglobular clouds. Cosmological simulations on such small scales are at the moment beyond the capabilities of available computer resources, since they require a very large dynamical range.

ACKNOWLEDGEMENTS

We thank S.M. Fall and A. Kashlinsky for fruitful comments and discussions during the elaboration of this manuscript. We also enjoyed discussions with C. Flynn, C. Lacey & B. Pagel. We are thankful to the referee, Dr. Joe Silk, for helpful comments on the paper.

We are grateful to Michele Cavigioli for providing special computer facilities in Copenhagen.

The work has been partly supported by the Danish National Research Foundation through its support for the establishment of the Theoretical Astrophysics Center.

REFERENCES

Aguilar, L., Hut, P., Ostriker, J.P. 1988, ApJ, 335, 720
Arp, H.C., Baum, W.A., Sandage, A.R. 1952, AJ, 57, 4
Ashman, K. E. 1990, MNRAS, 247, 662
Ashman, K. E., Zepf, S. E. 1992, ApJ, 384, 50
Bahcall, J.N., Soneira, R. 1984, ApJS, 277, 27
Bahcall, J.N., Flynn, C., Gould, A., Kirhakos, S. 1994, ApJ, 435, L51
Beers, T. C., Sommer-Larsen, J. 1995, ApJS, 96, 175
Brown, J.H., Burkert, A., Truran, J.W. 1991, ApJ, 376, 115
Brown, J.H., Burkert, A., Truran, J.W. 1995, ApJ, 440, 666
Carlberg, R.G. 1981, MNRAS, 197, 1021
Charlton, J. C., Laguna, P. 1995, ApJ, 444, 193
Duerr, R., Imhoff, C.L., Lada, C.J. 1982, ApJ, 261, 135
Dove, J.E., Mandy, M.E. 1986, 311, L93
Fahlman, G.G., Richer, H.B., Searle, L., Thompson, I.B. 1989, ApJ, 343, L49
Fall, S. M. 1978, Globular Clusters
Fall, S. M., Rees J. M. 1985, ApJ, 298, 18
Gunn, J. E. 1977, ApJ, 218, 592
Hanes, D. E. 1977, Mem. RAS, 84, 45
Harris, W. E. 1991, ARA&A, 29, 543
Harris, W. E. 1995, ApJ
Harris, W. E., Racine, R. 1979, ARA&A, 17, 241

© 0000 RAS, MNRAS 000, 000–000
Harris, W. E., Pudritz, R. E. 1994, ApJ, 429, 177
Hirasawa, T. 1969, Prog. Theor. Phys., 42, 523
Hirasawa, T., Aiza, K., Taketani, M. 1969, Prog. Theor. Phys., 41, 835
Hut, P., Djorgovski, S. 1992, Nature, 359, 806
Hutchins, J.B. 1976, ApJ, 205, 103
Iben, I., Renzini, A., 1984, Phys. Rep. 105, 329
Jacquin, L., Cambon, C., Blin, E. 1993, Phys. Fluids A 5, 2539
Jimenez, R., Thejll, P., Jørgensen, U., MacDonald, J., Pagel, B. 1996, MNRAS, in press
Kang, H., Shapiro, P.R., Fall, S. M., Rees, M. J. 1990, ApJ, 363, 488
Kolb, E.W., Turner, M.S. 1990, The Early Universe, Addison-Wesley
Kumai, Y., Basu, B., Fujimoto, M. 1993, ApJ, 404, 144
Lada, C. J., Lada, E. A., Clemens, D. P., Bally, J. 1994, ApJ, 429, 694
Larson, R. B. 1969, MNRAS, 145, 271
Larson, R. B. 1969, MNRAS, 145, 405
Larson, R.B. 1973, Fund. Cosm. Physc. 1,1
Larson, R.B. 1986, in Nearly Normal Galaxies, ed. S. Faber (NY: Springer) p.26
Larson, R. B. 1990, In Physical Processes in Fragmentation and Star Formation, ed. R. Capuzzo-Dolcetta, C. Chiosi, A. Di Fazio, p.389. Dordrecht: Kluwer
Lepp, S., Shall, J. M. 1983, ApJ, 270, 578
Matteucci, F., Greggio, L. 1986, A&A, 154, 279
Matsuda, T., Sato, H., Takeda, H. 1969, Prog Theor. Phys., 42, 219
Miller, G. E., Scalo, J. M. 1979, ApJS, 41, 413
Mooney, T.J., Solomon, P.M. 1988, ApJ, 334, L51
Myers, P.C., Dame, T.M., Thaddeus, P., Cohen, R.S., Silverberg, L.F., Nordlund, Å., Padoan, P. 1996, submitted to Physics of Fluids.
Norris, J. 1986, ApJS, 61, 667 Dwek, E., Hauser, M.G. 1986, ApJ, 301, 398
McWilliam, A., Rich, R.M. 1994, ApJS, 91, 749
Ostriker, J. P. 1986, in The Harlow-Shapley Symposium on Globular Clusters Systems in galaxies, eds. Grindlay, J.E. and Davis Philip, A.G.
Palla, F., Zinnecker, H. 1988, in IAU Symposium 126: The Harlow-Shapley Symposium on Globular Clusters Systems in galaxies, ed. J.E. Grindlay and A.G.D. Philip (Dordrecht:Reidel), p. 323
Palla, F., Salpeter, E.E., Stahler, S.W. 1983, ApJ, 271, 632
Padoan, P. 1995, MNRAS, 277, 377
Padoan, P., Nordlund, Å. P., Jones, B. J. T. 1996, submitted to ApJ.
Padoan, P., Jones, B. J. T., Nordlund, Å. P. 1966, submitted to ApJ.
Nordlund, Å., Padoan, P. 1996, submitted to Phys. Fluids
Peebles, P.J.E., Dicke, R.H. 1968, ApJ, 154, 891
Peebles, P.J.E., 1984, Science, 224, 1385
Richer, H.B., Fahlman G.G., Buonanno, R., Fusi Pecci, F., Searle, L., Thompson, I.B. 1991, ApJ, 381, 147
Richer, H.B., Fahlman G.G. 1992, Nature, 358, 383
Rosenblatt, E. L., Faber, S. M., Blumenthal, G. R. 1988, ApJ, 330, 191
Rotman, D. 1991, Phys. fluids, A 3 (7), 1792
Schmidt, M. 1963, ApJ, 137, 758
Searle, L., Zinn, R. 1978, ApJ, 225, 357
Shapiro, P., Kang H. 1987, 318, 32
On star formation in primordial protoglobular clouds.

Shu, F.H. 1977, ApJ, 214, 488
Silk, J. 1977, ApJ, 211, 638
Spitzer, L. Jr. 1978, in Physical Processes in the Interstellar Medium (New York:John Wiley)
VandenBerg, D.A., Bolte, M., Stetson, P.B. 1990, AJ, 100, 445
Vietri, M., Pesce, E. 1995, ApJ, 442, 618
van den Bergh, S. 1962, AJ, 67, 486
van den Bergh, S. 1993, ApJ, 411, 178
Wheeler, J.C., Sneden, C., Truran, J.W., 1989, ARA&A, 27, 279
Woltjer, L. 1975, A&A, 42, 109
Zinnecker, H., Keable, C.J., Dunlop, J.S., Cannon, R.D., Griffiths, W.K. 1988. In Globular Clusters Systems in Galaxies, IAU Symp. No. 126, ed. J. Grindlay, A.G.D. Philip, p. 603. Dordrecht:Reidel