Astronomy Letters, Vol. 21, No. 4, 1995, pp. 508 - 512. Translated from Pis'ma v Astronomicheskii Zhurnal, Vol. 21, No. 8, 1995, pp. 574 - 579.

Star Clusters as a Source of Field Stars in the Galactic Halo

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Received January 31, 1995

Abstract – The origin of stars in the Galactic halo is discussed. The current globular cluster disruption rate is entirely inadequate for this. An attempt is made to reconstruct the initial mass function for globular clusters and estimate the total initial mass of their populations; but even this mass ($\sim 10^8\ M_\odot$) is less than the mass of the stellar population of the Galactic halo ($\sim 10^{10}\ M_\odot$). One additional possibility is to take account of stars in associations initially not bound to the clusters but accompanying them. However, at the present level of cluster formation efficiency (~10%), an estimate of the total initial mass of the stellar population accompanying globular clusters ($\sim 10^9\ M_\odot$) is also not sufficient to explain the origin of field stars. For these reasons, we investigate the possible formation of a special low-mass population of star clusters during the period of proto-Galactic collapse, which has since been entirely disrupted. The origin of Galactic halo field stars can be explained using such a scenario.

INTRODUCTION

Amongst questions connected with the origins of the Galaxy, one of the most interesting is the formation of its stellar halo and the interactions between its components. Properly speaking, there are in all two components: field stars and globular cluster stars. They have some common properties (low metallicity, a similar spatial distribution) but there are differences between them as well; for example, some stars in the field show significantly lower metallicities than those in clusters. It would be possible to answer many questions about the genesis of the stellar halo using accurate data on the ages, chemical compositions, and kinematics of field and cluster stars; however, there is not yet a sufficient quantity of such data. It is not yet possible to uncover the relation (if one exists) between age and metallicity for field stars, and between metallicity, mass, and kinematics for globular clusters. Therefore, one of the paths by which we may approach an understanding of the history of the halo is theoretical reconstruction of the evolution of globular clusters and consideration of alternative possibilities for the origin of field stars, both associated and not associated organically with globular clusters.

In this article, we estimate the rate of appearance of stars in the halo field due to disruption of globular clusters; we attempt to reconstruct the initial mass of the system of globular clusters; and we estimate the total mass of stars formed in the process of globular cluster formation, using toward these ends certain analogies with the present formation of open clusters and associations. The results obtained in this way point toward the need to search for an additional source for the halo field stars. It seems to us that such a source could be a large population of low-mass star clusters, formed in the period of collapse of the proto-Galaxy and which have since almost completely disappeared. The possibility of formation of such clusters in the required numbers is indicated by a consistent treatment of the process of gravitational instability in the turbulence of the proto-Galaxy and the subsequent evolution of gaseous clouds and stellar aggregates. Of course, the unresolved question of the origin of the globular clusters remains; but in the given case this problem recedes as a secondary issue.

GLOBULAR CLUSTER DISRUPTION RATE

Amongst the numerous reasons for disruption of globular clusters, the most important at our epoch are gravitational shocks attendant to intersection with the Galactic plane; dynamical friction, leading to compression of orbits; and also the evaporation of stars from the cluster. In addition, these effects are significantly strengthened by the influence of the tidal field of the Galaxy (Aguilar *et al.* 1988; Chernoff and Weinberg 1990; Surdin 1978, 1979, 1993, 1994a). As a result of these processes, well-known correlations have arisen between the galacto-centric distance of globular clusters and their dynamical parameters – such as their half-mass radii (van den Bergh *et al.* 1991; Surdin 1994a), the minimum value for the King concentration parameter (Surdin 1992, 1993; Djorgovski and Meylan 1994), and the maximum and minimum values of the cluster mass (Surdin and Charikov 1977; Surdin 1978; Tremain *et al.* 1975).

It is of fundamental importance that evolution of the system of globular clusters and the appearance of the indicated correlations occurred, in the main, not as a result of changes in the parameters of individual clusters, but rather as a result of complete disruption of some and preservation of other members of the system. This significantly complicates the reconstruction of the initial parameters of the system of globular clusters,

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in particular, their total numbers and mass. Therefore we first consider the most conservative alternative for the history of clusters, supposing that their numbers never exceeded their present values. At our epoch, the flux of stars into the Galactic halo is mainly determined by evaporation (dissipation) of clusters. For every one of them, this flux S is

$$S = \frac{\xi_e M}{t_{rh}}, \quad (1)$$

where M is the mass of the cluster, t_{rh} is the relaxation time at the half-mass distance from the center of the cluster (r_h), and ξ_e is a constant whose value lies somewhere in the range 0.8 to 4.2% depending on the extent to which the cluster is tidally bound by the field of the Galaxy, its degree of concentration, the mass function of its stars, the presence of binary systems, etc. (Spitzer 1990). For our estimates it is sufficient to use $\xi = 2\%$. Using the expression for t_{rh} from the work of Spitzer (1990) and taking the average mass of stars in a cluster to be 0.3 $M_\odot$, we obtain

$$S = 4 \times 10^{-8} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{r_h}{1\ \mathrm{pc}}\right)^{-3/2} M_\odot\ \mathrm{yr}^{-1}. \quad (2)$$

For calculation of S, we used data for 96 Galactic globular clusters (van den Bergh *et al.* 1991, Djorgovski 1993), and converted the measured values for the half-luminosity diameter (the diameter containing half the luminosity projected onto the sky) ($D_{0.5}$) to the radius r_h (Spitzer 1990): $D_{0.5} \cong 1.5 r_h$. For the majority of clusters, we obtained $S \sim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$. The maximum rate of evaporation $S_{max} = 4 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ was found for NGC6440 and the minimum rate $S_{min} = 7 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ was found for NGC5053. Summing over all clusters, we obtain $S_{sum} = 4 \times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$. Considering that our sample was made up of roughly half the entire number of Galactic globular clusters (Surdin 1994b), it is possible to estimate the their total disruption rate: $S_{tot} \approx 8 \times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$.

Note that throughout this paper we take $M/L_V = 2.3$ for globular clusters, based on the data of Pryor and Meylan (1993), who determined this value from the velocity dispersions of stars in 56 clusters. The full range of M/L_V values was found in that work (0.5 - 6.2), but most them were grouped in the region from 1 to 4, and had a weighted average of 2.3 ± 0.9.

For the majority of globular clusters in existence today, the time required for half the cluster to evaporate ($t_{ev} \approx 70\ t_{rh}$) significantly exceeds the age of the Galaxy ($H_0^{-1} \approx 17 \times 10^9$ yr). Therefore, the evaporation rate does not change significantly with time, and the total mass lost in stars may be estimated as $S_{tot} H_0^{-1} \approx 1.4 \times 10^7\ M_\odot$. For comparison, the total mass of the 147 Galactic globular clusters studied to date is $4 \times 10^7\ M_\odot$. Taking undiscovered clusters into account, this value probably approaches $5 \times 10^7\ M_\odot$. It follows that, over the period of its quasi-steady evolution, the existing system of globular clusters has lost only an insignificant fraction of stars and has not noticeably enriched the field of the Galactic halo.

THE INITIAL MASS OF THE GLOBULAR CLUSTER SYSTEM

In order to estimate parameters for the initial population of Galactic globular clusters, it is necessary to make certain assumptions; for example, that there exists a subsystem of clusters that have been practically untouched by evolution. Indeed, it is possible to identify such a subsystem: in the region with Galactocentric distances $R_g \geq 5$ kpc and masses $M \geq 10^5\ M_\odot$, the effects of evolution are weak. Therefore, it is likely that the cluster mass spectrum for this subsystem has preserved its initial form and may become the basis for the establishment of the characteristics of the original population.

Ignoring the tradition of describing the mass spectra of globular clusters using Gaussian functions, Surdin (1979) and Racine (1980) showed that in the region of weak evolutionary effects both in the Galaxy and in M31, the globular cluster mass spectra have a simple power-law form: $dN/dM \propto M^{-2}$. This was later confirmed using more modern data (Richtler 1992). It is important that the power-law spectra does not have an isolated characteristic value for the mass, which widens the range of possible scenarios for cluster formation. At the same time, this spectrum is not so steep as to lead to large errors in the estimate of the total initial mass of the cluster system.

In the region of weak evolutionary effects in the Galaxy ($R_g \geq 5$ kpc for $R_0 = 8.5$ kpc and $M \geq 10^5\ M_\odot$ for $M/L_V = 2.3$), the total mass in known globular clusters is $2.6 \times 10^7\ M_\odot$. Taking account of clusters that have not yet been discovered, it is probable that this mass is close to $3 \times 10^7\ M_\odot$. 60% of all clusters having $M > 10^5\ M_\odot$ have $R_g > 5$ kpc. Considering that the most massive clusters in the region $R_g \leq (3 - 4)$ kpc have been disrupted under the action of dynamical friction, we may estimate the fraction of massive clusters in the region $R_g < 5$ pkc with acceptable accuracy to be 50%. Thus, in the range of masses from $3 \times 10^6\ M_\odot$ (the most massive cluster – ω Cen) to $10^5\ M_\odot$, the total cluster mass is roughly $6 \times 10^7\ M_\odot$.

Continuing the cluster mass spectrum indicated above to the region of low masses, we obtain an initial mass for the globular cluster system:

$$M_i(\mathrm{GC}) = 2.6 \times 10^8 \left[1 - 0.07 \ln\left(\frac{M_{min}}{M_\odot}\right)\right] M_\odot, \quad (3)$$

where M_{min} is the lower boundary for the spectrum. Since this result depends only weakly on M_{min}, we take this value to be close to the minimum mass for open clusters forming now, that is, $\sim 10^2\ M_\odot$ (Danilov and Seleznev 1994). In this case, the estimate for the initial mass of the globular cluster system is $M_i(\mathrm{GC}) \simeq 2 \times 10^8 M_\odot$. This is substantially smaller than the mass of stars in the Galactic halo. Consequently, assuming the same power-law spectrum for low masses as is observed for high masses ($dN/dM \propto M^{-2}$), we cannot explain the origin of stars in the halo only by the disruption of the globular cluster system.

THE "CLUSTER–ASSOCIATION" DICHOTOMY

In all galaxies that are accessible to detailed study, the formation of gravitationally-bound clusters is accompanied by the birth of stellar associations, having low density and rapidly breaking apart in the tidal field of the galaxy (see Efremov 1989). It would be strange if at the epoch of formation of the Galactic halo, the formation of gravitationally-bound (globular) clusters were not accompanied by the birth of analogous stellar associations. Therefore, the question of the origin of halo stars we now pose thus: is it possible that the field stars and clusters were formed in one process of star formation, keeping in mind that the birth of clusters is accompanied by the emergence of short-lived associations?

We intentionally do not broach here the subject of the mechanism of the birth of associations, since there exist several possible processes leading to the birth of groups of stars with positive total energy or, at any rate, instability in the Galactic field. For us, it is important that the formation of open clusters and the formation of associations accompany each other in space and in time, and in the Galactic disk these events occur with the same frequency: $\nu_{\mathrm{OC}} \simeq \nu_{\mathrm{A}} \simeq (2 - 4) \times 10^{-4}\ \mathrm{yr}^{-1}$ (Elmegreen 1983a). However, the characteristic mass of associations ($M_{\mathrm{A}} \sim 10^4\ M_\odot$) is an order of magnitude larger than the mass of clusters ($M_{\mathrm{OC}} \sim 10^3\ M_\odot$). Therefore, the current flux of stars in the field from associations is $\mathrm{SFR(A)} \simeq 3\ M_\odot\ \mathrm{yr}^{-1}$, which exceeds the flux from open clusters $\mathrm{SFR(OC)} \simeq 3\ M_\odot\ \mathrm{yr}^{-1}$ by an order of magnitude.

By analogy with the *star formation efficiency* (SFE) indicating the fraction of mass in a cloud becoming stars, it is useful to introduce the *efficiency of formation of gravitationally-bound systems*, or, more concisely, the cluster formation efficiency (CFE), indicating the fraction of mass in newly-born stars contained in long-lived systems – clusters. We define the current value of this quantity as

$$\mathrm{CFE} = \frac{\mathrm{SFR(C)}}{\mathrm{SFR(C)} + \mathrm{SFR(A)} + \mathrm{SFR(I)}}, \qquad (4)$$

where SFR(C), SFR(A), and SFR(I) are the frequencies of star formation in clusters, associations, and in isolated form (for example, in globules), respectively. Considering that isolated stars form relatively rarely (Zinnecker *et al.* 1993) and that stars are born much more often in associations than in clusters, it is possible to estimate the current cluster formation efficiency as $\mathrm{CFE} \simeq \mathrm{SFR(OC)/SFR(A)} \simeq 10\%$.

In the mathematical sense, the values of the SFE and CFE are close: the first describes the "gas–star" dichotomy while the second, if we do not concern ourselves with isolated stars, describes the "cluster–association" dichotomy. However the physical processes controlling these quantities are fundamentally different. The star formation efficiency is determined by the integral energetic relationships within the limits of the molecular cloud, and is not very sensitive to the specific distribution of gas and stars. Therefore, the SFE lends itself well to theoretical estimation, giving results that agree with observations (Surdin 1989). In contrast, the CFE depends directly on the relative distribution of stars and gas in the cloud volume, as well as on the velocity distribution of the stars (Surdin 1976; Elmegreen 1983b; Lada *et al.* 1984; Pinto 1987). These quantities do not lend themselves to theoretical estimation. Therefore, we may only establish a current average value for the $\mathrm{CFE} \simeq 10\%$, with no possibility of theoretically estimating its value under the initial conditions.

Assuming that the formation of globular clusters was accompanied by the birth of stellar associations with the same efficiency as at our epoch (CFE = 10%), we estimate the total mass of stars forming in this process:

$$M_{\mathrm{tot}}(\mathrm{GC + A}) = \frac{M_i(\mathrm{GC})}{\mathrm{CFE}} \simeq 2 \times 10^9\ M_\odot. \qquad (5)$$

This value is the maximum that can be expected under reasonably conservative assumptions about the process of star formation in which the globular clusters known to us arose. But the mass of the stellar population of the spherical subsystem (bulge + halo) is $\sim 10^{10}\, M_\odot$ (Edmunds and Phillips 1984; Haud *et al.* 1985), i.e., it is several times greater than $M_{\mathrm{tot}}(\mathrm{GC + A})$. There are at least two possible ways to resolve this contradiction: suppose that in the period of star formation, the halo CFE was ~1%; or suppose an additional mechanism for the formation of stars in the halo that would yield a large output of stellar mass but not lead to the appearance of long-lived clusters. There is currently nothing on which to base such a small value for the CFE; therefore, we consider the possible birth in the halo of low-mass clusters that would be entirely dissipated by the present time.

THE FORMATION OF STELLAR CLUSTERS IN THE TURBULENT PROTO-GALAXY

In various theories of globular cluster formation, the large masses of globular clusters (10^4 - $10^6\ M_\odot$) are the result of the low density of gas in the halo or in the pre-Galactic medium (Peebles 1984; Fall and Rees 1985; Murray and Lin 1992). However, this density may be enhanced locally by the compression of gas in shock waves. There are indications that the collapse of the

Galactic halo took place over a time scale of $\sim 3 \times 10^9$ yr (Yoshii and Saio 1979), so that its quasi-equilibrium was maintained by powerful turbulent motions characterized by supersonic speeds, due to the short cooling time of the gas. The behavior of the gas under such conditions was considered by Sabano and Tosa (1983). It turns out that behind the shock wave front, the compressed and cooled gas has values for the Jeans mass and radius equal to: $M_J \approx 3 \times 10^5 M_\odot$, $R_J \approx 50$ pc. Noting the closeness of these values to the parameters of globular clusters, Sabano and Tosa (1983) decided that they were the precursors of globular clusters; not attaching importance, for example, to the fact that in present-day molecular clouds with similar parameters, only low-mass open clusters form.

Here we come up against a fundamental question: how to compare the theoretical parameters of proto-clusters (for example, the Jeans parameters of the gas) and the characteristics of stellar clusters? Along the way from gas proto-cluster to stellar cluster there are several important evolutionary transitions: 1) the "gas–stars" dichotomy; 2) the "cluster–association" dichotomy; and 3) the first intersection with the region of maximum tidal field (for open clusters this is the plane of the Galaxy, while for globular clusters it is the region of peri-center of the orbit). Under present conditions, the first transition decreases the mass of the proto-cluster by a factor of 10^2 (SFE ~ 1%); the second decreases mass by an additional factor 10 of (CFE ~ 10%); and the third, apparently, is not very important for open clusters (although this must still be investigated) but may be significant for globular clusters, with their elongated orbits. However, for the aims of this paper, as will be seen, it is entirely adequate to take only the "gas–stars" dichotomy into account.

For a cloud of mass M_c and radius R_c, the gravitational binding energy is $|U_c| = GM_c^2/R_c$. We estimate the mass of the stellar aggregate M_s which, having formed in the cloud, is capable of disrupting it and stopping the process of star formation. We write the contribution of this aggregate to the energy of the cloud as

$$E = \mu \varepsilon M_s, \qquad (6)$$

where ε is the energetic output of massive stars (in the form of radiation, wind, and possibly, kinetic energy in the shells of supernovae) per unit mass of aggregate, and μ is the fraction of this energy remaining for a long time in the hot "bubble" around the star-forming region. The cloud disrupts under the obvious condition:

$$|U_c| = E. \qquad (7)$$

For $\varepsilon = 10^{49}$ erg/$M_\odot$ and $\mu = 0.1$ (Larson 1974; Tenorio-Tagle *et al.* 1990), we obtain from (7)

$$M_s = 10^4 M_\odot \left(\frac{M_c}{10^6\ M_\odot}\right)^2 \left(\frac{R_c}{10\ \mathrm{pc}}\right)^{-1}. \qquad (8)$$

For present-day molecular clouds ($M_{GMC} \approx 10^6 M_\odot$, $R_{GMC} \approx 20$ pc), formula (8) gives a reliable estimate of the mass of the aggregate of new-born stars, including future clusters and associations: $M_s \approx 5 \times 10^3 M_\odot$. Therefore, we may hope that this expression is applicable to the process of star formation in the halo as well. In particular, using it to estimate the mass of stars in Sabano–Tosa proto-clusters of (assuming, in accordance with the virial theorem, that their equilibrium radius was $R_c \approx 0.5 R_J$), we obtain $M_s \approx 400\ M_\odot$. Thus, the model of Sabano and Tosa (1983) actually predicts the formation of clusters with masses close to those of present-day open clusters rather than of globular clusters. Even if the cluster formation efficiency at that epoch was high (CFE ~ 100%), these low-mass clusters should have completely dissipated over cosmological time. The minimum mass of halo clusters capable of being preserved up to the present time is (Surdin 1978):

$$M_{\min} = 2 \times 10^4 \left(\frac{R_p}{1\ \mathrm{kpc}}\right)^{-1} M_\odot, \qquad (9)$$

where R_p is the peri-Galactic distance for the cluster orbit. Consequently, a cluster with mass $M_s = 400\ M_\odot$ can be preserved only at a distance of more than 50 kpc from the Galactic center. It is not excluded that certain distant low-mass halo clusters (Pal11, Pal13, AM4) are related to precisely this population.

We estimate the total number of Sabano–Tosa proto-clusters (N) by supposing that the gravitational energy of the Galaxy was scattered by shock waves in the turbulent halo:

$$N = \left(\frac{M_G}{M_J}\right)\left(\frac{V_\infty}{V_t}\right)^2. \qquad (10)$$

Here M_G is the mass of the Galactic stellar population, V_∞ is the mean velocity of escape from the Galaxy (with the dark coronal matter taken into account), and V_t is the characteristic velocity of turbulent motion. For $M_G = 10^{11} M_\odot$ (Haud *et al.* 1985), $V_\infty = 650 \pm 50$ km/s, $M_J = 3 \times 10^5 M_\odot$, and $V_t = 100$ km/s (Sabano and Tosa 1983), we obtain $N \approx 2 \times 10^7$, and the total mass in stars $M_{st} = M_s N = 8 \times 10^9 M_\odot$. This is several times larger than the expected initial mass of the globular cluster system, and together with it leads to an expected mass for the stellar halo $M_H = M_{st} + M_i(\mathrm{GC}) = 10^{10} M_\odot$, in full agreement with observations.

CONCLUSION

We have shown that the fundamental mass of stars in the halo cannot be related to the disruption of existing globular clusters, even taking the full disruption of low-mass part of this population into account. We also considered the possibility of the existence of stellar associations that formed together with the globular clusters. For a cluster formation efficiency close to the present value, the expected total mass of associations exceeds the cluster mass by an order of magnitude, but, all the same, falls significantly short of the observed mass of halo stars. We therefore considered the possibility of formation of an independent population of low-mass clusters that should be completely disrupted by the current epoch. This possibility exists: it follows from a model for cloud formation and subsequent star formation in the turbulent proto-Galaxy. The expected total mass in stars in this model agrees with the observed mass for the stellar halo of the Galaxy.

The question of the origin of the globular clusters themselves has been "swept under the rug" in this discussion. It is clear that its answer cannot be limited to one process for star formation, as has been imagined until recently. Now theories of globular cluster formation in the pre-Galactic epoch (Peebles 1984; Rosenblatt *et al.* 1988), in the period of formation of the cluster of galaxies (Jones *et al.* 1981), in the period of formation of the Galaxy itself (Fall and Rees 1985; Murray and Lin 1992, Vietri and Pesche 1995), and in the modern epoch (Ashman and Zepf 1992) are being developed. It is not excluded that each epoch gave its own contribution to the globular cluster system – there are more than a few indications that it is inhomogeneous. But in the development of any one of these theories it is essential to remember the important evolutionary transitions from cloud to cluster which we have indicated. Only a consistent account of these transitions, as was shown, leads to a realistic estimate of the mass of clusters and their population as a whole.

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