THE FORMATION OF GLOBULAR CLUSTERS AND OF THE STARS WITHIN THEM

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We propose that proto-globular cluster clouds form in a collapsing protogalactic cloud as a consequence of thermal instability. The clouds are photoionized and heated by nearby massive stars. Most are not self-gravitating, but are confined by the residual hot gas in the protogalactic cloud. Their masses evolve as they undergo cohesive collisions with each other and erosion due to interaction with the residual halo gas. Collisions may also trigger thermal instability and fragmentation within protocluster clouds. The resulting cloudlets are pressure confined, and fall toward the center of the protocluster cloud due to inverse buoyancy. Their mass distribution is also regulated by coagulation and erosion. While most cloudlets have substellar masses, the largest become self-gravitating, and collapse to form protostellar cores without further fragmentation. The initial stellar mass function is established as these cores capture additional residual cloudlets. Energy dissipation from the mergers ensures that the cluster will remain bound in the limit of low star formation efficiency. Dissipation also promotes the formation and retention of the most massive stars in the cluster center.

1. Introduction

Globular clusters contain the oldest stars in the Galaxy. Investigations of the formation of these clusters and the stars within them can therefore provide important clues regarding the origin and evolution of the Galaxy. Our main objective here is to provide an overview of some recent developments in the theory of cluster formation, and their implications in terms of a comprehensive unified theory.

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2. Fragmentation of Protogalactic Clouds

Our basic conjecture is that globular clusters formed within infalling protogalactic clouds (PGC's) (see, e.g. Fall & Rees 1985). During the collapse of a PGC, density inhomogeneities and velocity variations lead to shocks which heat the gas to the virial temperature of the galactic halo (Binney 1977; Rees & Ostriker 1977; White & Rees 1978). In order for a PGC to collapse, its cooling time scale, τ_c, must be shorter than the dynamical time scale, τ_d, on which it can contract. For systems with masses comparable to the Galaxy, this condition is satisfied when the characteristic length scale of the PGC, $D < 100$ kpc (Blumenthal *et al.* 1984).

Subsequent fragmentation of the PGC requires the growth of density inhomogeneities on a time scale, $\tau_g < \tau_d$. If the PGC is cold, gravitational instability causes perturbations with initial amplitude δ_0 to become nonlinear when the system collapses by a factor $\sim \delta_0^{2/3}$ (Hunter 1962). Even if $D = 100$ kpc, the initial perturbations must be nearly nonlinear for gravitational instability to trigger fragmentation of the PGC at a few kpc. Such a requirement is difficult to satisfy on scales much smaller than D.

Thermal instability can, however, lead to the rapid growth of perturbations, even in the limit of infinitesimal δ_0, when $\tau_c < \tau_d$ (Field 1965). At the virial temperature of the PGC, the dominant cooling mechanisms are bremsstrahlung and recombination processes (Dalgarno & McCray 1972) for which τ_c increases with temperature. In this case, the temperature difference between cooler perturbed regions and the background is amplified and a pressure gradient across the interface is established. The resulting gas flow from the hot background towards the cooler perturbed regions further acts to decrease τ_c rapidly from $\sim \tau_d$ at the onset of thermal runaway to $\ll \tau_d$.

Fragmentation of a cloud requires instabilities for which the growth time scale, τ_g, increases with wavelength, λ. For thermal instability associated with local cooling, τ_g is independent of λ. During the growth of thermal instability, however, pressure balance is maintained on scales smaller than that (l_s) traveled by sound on a time scale τ_c. Compact ($< l_s$), cool dense regions contract as entropy is lost at a much faster rate than the background. Since τ_c increases with temperature, the interface separating cool regions and the background retreats at an accelerating pace, leading to the growth of Rayleigh-Taylor instability, for which τ_g is an increasing function of the wavelength (Burkert & Lin in preparation). The acceleration of the interface increases as the temperature in the perturbed region decreases. The long wavelength disturbances become stabilized when their growth time scales become long compared with that over which the acceleration of the interface is modified. Nevertheless, they grow to nonlinearity due to the Richtmyer-Meshkoff instability. As the temperature in the perturbed regions continues to plummet, l_s decreases rapidly to below the length scale of the perturbed regions, and so most parts of the perturbed region cool without any significant change in density. Pressure balance is, however, enforced and Rayleigh-Taylor instability grows within l_s from the interface.

Bremsstrahlung, recombination, and atomic hydrogen emission decrease rapidly in efficiency below $\sim 10^4$ K. In even a metal-free PGC, however, non-equilibrium recombination leads to the formation of a small amount of H^- ions which combine with neutral H to form H_2. Radiative emission by H_2 reduces the gas temperature to $\sim 10^2$ K (Murray & Lin 1990). If $[Fe/H] > -3$, lower temperatures (~ 10 K) are attainable due to cooling by heavy elements (e.g. CI, CO, and grains). Equilibrium temperatures $\sim 10^4$ K may be maintained in the presence of external heat sources (see § 3). Once the final temperature is attained, pressure balance is re-established on all scales. The PGC becomes a two-phase medium with density contrast inversely proportional to the temperature difference. The residual halo gas (RHG) in the background remains at the virial temperature, with a density such that its thermal energy is lost on a time scale $\sim \tau_d$. Energy loss from the RHG can occur through both radiative cooling and thermal conduction between the RHG and the cool, dense clouds (McKee & Cowie 1977). At the distance of ~ 10 kpc, the energy balance implies $nT \sim 10^3 - 10^4$ where n and T are the halo number density and temperature.

Most of the cool dense clouds are pressure confined by the RHG, and so have similar nT. The RHG also exerts a drag on the motion of the clouds as they are accelerated by the gravity of the Galactic halo. The terminal speed of clouds with size L is $V_t \sim (f_n L/D)^{1/2} V_k$ where f_n is the density ratio of the clouds to the RHG, and V_k and D are the velocity dispersion and size of the halo, respectively. The motion of the clouds through the RHG also leads to mass loss due to Kelvin-Helmholtz instability (Murray *et al.* 1993), whose growth time scale (τ_{KH}) is a few times L/V_t. Because τ_{KH} increases with λ, the KH instability leads to fragmentation. The break down of the clouds increases their collective area filling factor and so increases their collision frequency. A balance between disruption and coagulation establishes an equilibrium size distribution.

3. Formation of Protocluster Clouds

A lower limit on their size distribution is set by the clouds' evaporation due to conduction from the hot RHG. The central density of these clouds increases with their mass. In the high mass limit, the clouds' self-gravity suppresses the Kelvin-Helmholtz instability. But at a critical mass $M_c \sim T^2/(nT)^{1/2} M_\odot$, thermal pressure can no longer support the weight of the envelope (Bonner 1956), and the clouds undergo inside-out collapse (Shu 1977). During the collapse, although the Jean's mass decreases with density, it is larger than the mass contained inside any radius. The collapse is stable and does not lead to fragmentation without any further unstable cooling. Thus, contrary to the opacity-limited fragmentation scenario (Hoyle 1953; Low & Lynden-Bell 1976), M_c represents the minimum mass for isothermal collapsing clouds (Tsai, in preparation).

In a metal-free environment, $T \sim 10^2$ K and $M_c \sim 10 - 10^2 M_\odot$. The resulting massive stars are, however, copious sources of UV radiation. A population of $\sim 10^4$ O5 stars is adequate to photoionize the entire PGC out to 100 kpc. Photoionization raises $T \sim 10^4$ K and $M_c \sim 10^6 M_\odot$. Small (a few $M_\odot$) heated clouds are stable and star formation is quenched. As the massive stars evolve off the main sequence, the UV flux diminishes, cooling again leads to $T \sim 10^2$ K in sheltered regions, and spontaneous star formation is resumed. This self-regulated star formation scenario has three implications: 1) Stars formed in a metal-poor environment are massive and short-lived, consistent with their rarity today. 2) The elemental abundance distribution are produced by type II supernovae, consistent with that observed among stars with $[\mathrm{Fe/H}] < -1$ (Wheeler *et al.* 1989). 3) The self-regulated star formation rate naturally yields $[\mathrm{Fe/H}] \sim 0.1$ on the collapse time scale $\tau_d \sim 1$ Gyr, consistent with the halo stars.

The magnitude of M_c for the warm ($\sim 10^4$ K) clouds is comparable to the mass of globular clusters. We refer to these warm, massive clouds as protocluster clouds (PCC's). PCC's with mass $(M) < M_c (\sim 10^6 M_\odot)$ are confined by the RHG. These PCC's are completely photoionized by a single O5 star at a distance greater than their size (typical a few pc). They would persist for a significant fraction of τ_d if the accretion of smaller clouds can compensate for their mass loss due to stripping by the RHG. To verify that the PCC's were pressure-confined, we first estimate their nT from the current properties of globular clusters, averaged over their half-mass radius (r_h). We use these because n and the velocity dispersion at r_h do not change significantly during post-formation evolution. Extrapolation to the stage prior to star formation is, however, highly uncertain. If, after their formation, the stars undergo collapse and virialization from rest, the clouds' initial radii (r_i) would be $\sim 2r_h$. Larger r_i would be expected if star formation requires dissipative collisions and coagulation of substellar fragments (see § 4). But r_i is unlikely to be larger than the tidal radii of the PCC's, which are typically a few times larger than r_h. Thus, the initial density of the PCC's may be 1-3 orders of magnitude smaller than the average cluster density at r_h today. Based on the present velocity dispersion of the clusters, we infer the initial temperature of the PCC's to be $\sim 10^4$ K, comparable to that expected if they were photoionized. From these estimates, we infer $nT \sim 10^{2-5}$, and that $nT \propto D^{-3}$ where D is the cluster's distance to the Galactic center. In accordance with the pressure confinement scenario, both the magnitude and the spatial dependence of PCC's nT are consistent with those expected for the RHG (Murray & Lin 1992). ¿From these results, and the cluster metallicities, we can also estimate the cooling time scale (τ_{cc}) and dynamical time scale (τ_{dc}), of the PCC's. The ratio τ_{cc}/τ_{cd} increases from $\sim 10^{-4}$ near the Galactic bulge to ~ 1 at ~ 100 kpc. In most PCC's, $\tau_{cc} << \tau_{cd}$ and thermal equilibrium is only possible in the presence of external UV photons with a flux comparable to that required by self regulated star formation in the halo.

4. Induced Star Formation

A constraint on the duration of the star formation epoch can be imposed from the metal homogeneity (primarily in [Fe/H]) among stars within individual clusters. Based upon the color of the red giant branch, upper limits can be placed on the spread, Δ [Fe/H], ranging from 0.1 for metal poor clusters to 0.01 for metal rich clusters (Sandage & Katem 1977; Richer & Fahlman 1984). In M92, Δ [Fe/H]< 0.2, and [Fe/H]$= -2.2$ (Stetson & Harris 1988). With a mass $3 \times 10^5 M_\odot$, the total content of all metals in the cluster is $\sim 30 M_\odot$, representing the production of only a few supernovae. If star formation in M92 occurred over more than a few million years, supernovae would increase both [Fe/H] as well as Δ [Fe/H] to values much larger than observed.

The small Δ [Fe/H] implies that PCC's are well mixed and pre-enriched prior to a rapid burst of star formation. The most efficient mixing process within the PCC's is large scale turbulence (Murray & Lin 1990), which may be excited by the Kelvin-Helmholtz instability at the interface with the RHG. Since shock dissipation damps supersonic motion efficiently, the mixing time scale is typically a few $\tau_{dc} \gg \tau_{cc}$. External heating by nearby massive stars is then required to maintain a stable thermal equilibrium for the PCC's. Such an equilibrium is only stable, however, if the PCC's are not strongly self-gravitating.

In PCC's with marginal self gravity, mass loss due to ram pressure stripping by RHG is stabilized. Mass loss may also be compensated by coagulation in a collisional equilibrium. Collisions also introduce perturbations which, with a sufficiently large amplitude, could increase the cooling efficiency (Murray & Lin 1989). If the new state is thermally unstable, runaway cooling would lead to T <100 K. Once the PCC's re-establish pressure equilibrium, their n increases by the same factor by which T is reduced. Density enhancement increases the recombination rate and opacity, which blocks the penetration of UV photons and external heating.

Coagulation may also increase the masses of the PCC's to a point where they become self-gravitating, at which point the heating and cooling equilibrium is no longer stable (Murray & Lin 1992). With sufficiently large column density, self-shielding may also act to prevent the heating of the PCC's interior. All of these effects indicate that there is a small range of mass over which the PCC's become thermally unstable and begin to collapse.

During collisions, PCC's dissipate much of the kinetic energy of their Galactic orbits. Today, the Galactic distance of most globular clusters is smaller than that of the Sun. Thus, while most of the clusters are members of a spheroidal population, their distribution implies that, like the disk, their progenitors have much lower specific energy than the PGC, as would result from collisional dissipation. The collisions which triggered the onset of thermal instability may also have lead to the separation of PCC's from dark matter as well as any older stars which may have formed within them and contributed to their prior enrichment.

The onset of thermal and subsequent dynamical instabilities induce the fragmentation of PCC's into small cloudlets analogous to the formation of PCC's within a PGC. The rapid growth of thermal instability results in a strong pressure imbalance between the cooling cloudlets and a tenuous, warm (10^4 K) residual gas (WRG). A pressure wave is therefore driven into the cloud, which is subject to Rayleigh-Taylor instabilities, leading to fragmentation of the PCC's into cold, dense, low-mass cloudlets, confined by the thermal pressure of WRG which is, in turn, in balance with that of the RHG. With the clusters' present metallicity, the cloudlets cool to ~ 10 K so that $M_c \sim 0.1 M_\odot$. The cloudlets' velocity dispersion is comparable to their sound speed, so that the system is dynamically cold. The inverse buoyancy of the cloudlets in the WRG therefore causes the system of cloudlets to collapse under their collective gravity.

During their infall, the cloudlets lose mass through ram pressure stripping and gain mass through coagulation. In a collisional equilibrium, a power-law size distribution is established. At the upper limit of the mass spectrum, the cloudlets' masses exceed M_c and they collapse to form protostellar cores. Since no additional fragmentation is expected, the minimum stellar mass is $\sim M_c$. Protostellar cores can continue to acquire additional mass as they merge with residual cloudlets. The observed number of stars in the range m to $m + \mathrm{d}m$ is usually approximated as $\frac{\mathrm{d}N_*}{\mathrm{d}m} \propto m^{-(1+x)}$. Such a power-law mass distribution is expected in idealized coagulation models (Nakano 1966; Kwan 1979; Silk & Takahashi 1979). Approximate asymptotic solutions of the coagulation equations indicate $x \approx 0$ if the collisional cross-sections are given by the geometric cross-sections of the particles, whereas $x \approx 1$ if encounters are strongly gravitationally focussed.

These values of x encompass much of the observed range for both open and globular clusters (Salpeter 1955; Miller & Scalo 1979; Scalo 1986; Francic 1989; Capaccioli, Ortolani, & Piotto 1991).

Numerical simulations of the coagulation of cloudlets in PCC's (Murray & Lin 1996) shows that the geometric cross section determines the collisional frequency between uncollapsed cloudlets leading to a relatively flat mass distribution. But the protostellar cores have compact sizes and their capture rate of residual cloudlets is strongly affected by gravitational focusing. In this case, the growth time scale is a decreasing function of the mass. A few massive cores rapidly grow prior to any significant mass increase among most other cores, leading to a steep initial mass function (IMF) for the protostellar cores. Collisions between the residual cloudlets and protostellar cores lead to the growth of the cores' mass and the dissipation of their relative motion, while global instabilities increase their velocity dispersion (Aarseth *et al.* 1988). In the final stage of the PCC's collapse, the velocity dispersion increases more rapidly than does the mass of protostellar cores, and the collisional frequency is once again determined by the geometrical cross section of the cloudlets, leading to a flattening of the IMF during the collapse. The final slope of the IMF is determined by whether or not most cloudlets have undergone collisions to form protostellar cores before gravitational focusing ceases to be important.

The growth of the most massive cores is terminated when their UV emission heats and ionizes nearby cloudlets. The most massive stars require many dissipative mergers, and so are preferentially formed in the cluster center. This expectation is in contrast to the implication of opacity-limited fragmentation scenario, in which the Jean's criterion suggests that the high mass stars are preferentially formed in low density environments.

After the first generation of stars are formed, the residual gas must be removed from the clusters to avoid self-contamination. Extrapolating from the present stellar population, a Salpeter IMF would imply at least several tens of early type stars within a typical globular cluster. The UV flux from these massive stars is sufficiently intense to photoionize the residual gas throughout a PCC (Tenorio-Tagle *et al* 1986). In the shallow potential of PCC's, the resultant internal heating leads to the formation of an expanding ionization wave which is efficient in clearing out the residual gas within a few 10^6 yr (Noriega-Crespo *et al.* 1989).

Unless more than half of the gas in PCC's is converted into stars, the removal of the gas on a time scale comparable to the dynamical time scale rapidly reduces the depth of the cluster's potential. In most cases, the disposal of residual gas would then lead to the disruption of the cluster (Lada *al.* 1984). If, however, young stars form through the coagulation of low mass cloudlets, energy dissipation resulting from the mergers leads to the resulting star clusters having radii much smaller than the original PCC's. It is therefore more likely that the newly formed clusters will remain gravitationally bound even in the limit of inefficient star formation. Numerical simulations show an order of magnitude reduction in the half mass radius of the star cluster formed through coagulation of a system of collapsing cloudlets (Murray & Lin 1996).

5. Comparison with present-day cluster and star formation

In the construction of the above comprehensive model for the formation of globular clusters and the stars within them, we used the observed dynamical and chemical properties of globular clusters as constraints. This model has many implications on the observational properties of young clusters. However, young globular clusters are only found in distant galaxies such as NGC 1275 (Holtzman *et al.* 1992), where they cannot presently be resolved. However, recent observations find that most stars in the Galaxy today form in clusters in which the time scale for star formation is quite short (Lada et al. 1991; Lada 1992). The central density of some young clusters are comparable to that of some globular clusters. In the Trapezium cluster, all the stars appear to have an age $< 10^6$ yr (Prosser *et al.* 1994) which is $\sim 2\tau_{dc}$. These time scales are consistent with the above model, in which star formation proceeds through a sequence of initial gas fragmentation, coagulation, protostellar collapse, and the clearing of residual gas. (There are exceptions such as IC 348, where star formation has persisted for many τ_{dc}, Lada & Lada, 1995). It is therefore of value to compare the implications of our model with the dynamical properties of nearby sites of ongoing star formation, to provide both supporting evidence and constraints upon the above picture of star formation.

Molecular clouds are clumpy on all scales (Scalo 1985; Zinnecker *et al.* 1993). Complex cloud substructure may also be inferred from the large dispersion, over a small field, in the observed extinction of the stars in the background cluster IC 5146 (Lada *et al.* 1994). (The extinction is equivalent to the surface density of the intervening clouds). These observations suggest that fragmentation occurs in the clouds prior to the gravitational collapse of individual protostellar cores as we have postulated above.

Magnetic fields, neglected in our cluster and star formation scenario, are observed to be important in regulating the structure of star forming regions today. In these regions, the velocity dispersions, which is correlated with the length scale of the substructures (Larson 1981), are often larger than the sound speed inferred from the transition temperature, but are comparable to the Alfvén speed (Heiles *et al.* 1993; Caselli & Myers 1995). In some regions, the dispersive motion of the clouds may be regulated by the interstellar magnetic fields. There are also, however, magnetic supercritical regions, where the magnetic field can no longer balance gravity. These are the regions where massive stars and small clusters are formed. The lack of polarization in the densest cores of molecular clouds suggest that magnetic fields are excluded from these regions (Goodman *et al.* 1995). The decoupling of the field from the protostellar clouds is equivalent to the loss of thermal support during a cooling instability, and may also lead to complex substructures (Terquem & Lin in preparation).

The mass function of dark cloudlets in star forming complexes such as Ophiuchus, Taurus, Orion (Scalo 1985), and L1630 (Lada *et al.* 1991) has a very similar power-law distribution. It is considerably flatter than that of the stellar IMF. The extrapolated collisional time scale for the small cloudlets is comparable to a few local dynamical time scales, and so their size distribution could arise naturally from a collisional equilibrium. The relatively flat mass spectrum is then consistent with that obtained from numerical simulations of the coagulation processes among protostellar cores (Murray & Lin 1996), and implies that the physical cross section determines the merger rate among the cloudlets. In contrast, gravitational focusing is more important for the capture of residual cloudlets by the collapsed stellar cores, and so the stellar IMF is steeper.

Shortly after the formation of protostellar cores, they are surrounded by the residual gas and appear as embedded sources. IR observations indicate that the embedded sources are strongly clustered (Greene *et. al.* 1994). These clusters are much more centrally condensed than the host cloud complex. Furthermore, the brightest embedded sources are usually found at the center of the clusters (Lada 1992). The luminosity segregation is consistent with the concept that protostellar cores form through dissipative mergers of small cloudlets, such that the most massive stars preferentially form in regions of high density where the collision frequency is greatest.

Finally, in older star forming regions, the young stellar objects emerge as T Tauri stars. In the Orion Nebula, T Tauri stars also appear to be clustered. The higher luminosity T Tauri stars are more centrally condensed than those with low luminosities (Prosser *et al.* 1994). In these regions, there is not sufficient time for post-formation dynamical evolution toward mass segregation. The observations are consistent with the more massive stars forming in dense, central regions. Since most of their kinetic energy is dissipated during the coagulation, these massive stars remain near PCC's center after the residual gas is cleared.

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