THE ORIGIN OF GLOBULAR CLUSTERS

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1. INTRODUCTION

The purpose of this article is to review some recent attempts to understand the origin of globular clusters. To put this in perspective, it may help to recall the analogous problem of the origin of galaxies. This splits into two parts. First, given a proto-galaxy with a specified mass and radius, how does it collapse, form stars and settle into a state of dynamical equilibrium? Richard Larson explored these topics in an important series of numerical simulations in the 1970s. Progress in this area brings into sharper focus a second set of questions that really has precedence over the first. Why did proto-galaxies have properties like the initial conditions in the collapse calculations and what distinguishes galaxies from structures on much larger and much smaller scales? Similar questions face us when we consider the origin of globular clusters. First, how did stars form in a proto-cluster, what was the efficiency, the initial mass function and so forth? It is appropriate that Larson has discussed these topics in the preceding article but here we are mainly concerned with the second kind of question: What is special about objects with masses of order 10^5-10^6 $M_\odot$ and dimensions of a few tens of parsecs?

2. DISRUPTION

One possible answer to the last question is that star clusters formed with a wide range of properties and that only those with a much narrower range of properties survived to the present. In this spirit, we once emphasized the gradual disruption of clusters by dynamical

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friction, tidal shocks and internal relaxation (Fall and Rees 1977). When the time scales for these processes are set equal to a Hubble time, they define a "survival triangle" in the mass-radius plane. Most globular clusters lie inside the triangle but any objects that formed well outside it would have been destroyed or severely damaged by now (This was also noticed by J. P. Ostriker, unpublished). Disruption is not a complete answer because dynamical friction sets an upper limit on the masses that increases with galactocentric distance whereas the observed luminosities of globular clusters show no such dependence (Caputo and Castellani 1984). Moreover, tidal shocks, which occur as clusters pass through a massive disk, would not have any effect in elliptical galaxies. Finally, there is some doubt as to whether internal relaxation leads to the complete disruption of clusters. Thus, although these stellar dynamical processes may have played some role in restricting the range of sub-galactic structures, they cannot by themselves account for the special properties of globular clusters.

Two other disruptive effects, tidal limitation and star formation are potentially more important than the previous ones and act on shorter time scales. To remain bound, a cluster must have a mean density that exceeds a value set by the tidal field of the parent galaxy. As the orbit of the cluster carries it closer to the galactic center, it will experience a stronger tidal field, and consequently, shed some stars. A cluster on a nearly radial orbit might even be destroyed, releasing all its stars into a field population. The expulsion of gas from a proto-cluster during star formation can lead to disruption in either of two ways. If more than half the total mass is removed quickly (i.e. in a time shorter than the internal crossing time), the proto-cluster, including the stars that formed in it, cannot remain bound. Alternatively, if any amount of mass is removed slowly, the proto-cluster will expand, and in the presence of a tidal field, release its least bound gas and stars. The expulsion of gas by stellar winds, HII regions and supernovae is thought to be important in star-forming regions in the galactic disk today. Its importance during the formation of globular clusters, however, is hard to quantify because we know almost nothing about the number of massive stars that were produced.

The discussion of disruptive effects is necessarily rather vague but it does raise two issues worth emphasizing at this point. First, globular clusters today may bear only a loose resemblance to their progenitors. This should be kept in mind when comparing any predictions of the initial masses and densities with observations. Second, many field stars in the spheroidal components of galaxies may be the debris of disrupted or failed globular clusters. The traditional view is that, if field stars and globular clusters share a common origin, they should, as populations, have the same space distributions, kinematics and chemical compositions. We must not, however, insist on complete similarity in all these respects because the likelihood of a cluster being disrupted depends on its position, orbital motion, stellar mass function and so forth. Oort (1965) estimated that the intial number of globular clusters was at least an order of magnitude larger than the present number. He supposed that the stars liberated from disrupted clusters would be strung out along families of tube orbits and those passing through the solar neighborhood would appear as "moving groups". Unfortunately, since there is some doubt as to the reality of the moving groups considered by Oort, the initial number of globular clusters must be regarded as a free parameter.

3. PRIMARY FORMATION

Theories in this subject can be classified as primary, secondary or tertiary depending on whether globular clusters are assumed to form before, during or after the collapse of proto-galaxies. We discuss each of these possibilities in turn. Primary formation, first suggested by Peebles and Dicke (1968), relies on the fact that the baryonic Jeans mass just after recombination is of order 10^5-10^6 $M_\odot$. This defines the smallest objects that can form by gravity alone in some cosmological pictures. In others, perturbations on small scales are damped out and the first objects to form are galaxies or clusters of galaxies. Globular clusters may have a primary origin in a universe dominated by weakly interacting particles with small random velocities, i.e., "cold dark matter" (Peebles 1984). In this picture, the initial spectrum of perturbations is a decreasing function of mass with negative curvature. The development of structure is roughly hierarchical on large scales but more complicated on small scales. Luminous objects are assumed to form by the dissipative collapse of baryons in the potential wells provided by the dark matter. The collapse occurs at redshifts of 2-4 on galactic scales and at redshifts of up to 10-20 on smaller scales. If globular clusters formed in this way, they would, at least initially, be surrounded by dark halos with masses of order 10^7-10^8 $M_\odot$.

There are several objections to the idea that globular clusters formed before the collapse of proto-galaxies. Each has a counter argument that may or may not seem convincing. First, galaxies contain very few objects with masses in the range above 10^6 $M_\odot$ where a continuum of structures might be expected. It is, however, conceivable that many of the objects more massive and therefore less dense than globular clusters were tidally disrupted. Second, globular clusters are more concentrated toward the centers of galaxies than the dark matter. A corrollary is that intergalactic clusters are extremely rare. These problems are alleviated by "biasing", which ensures that the perturbations destined to form globular clusters are located preferentially but not exclusively inside the perturbations destined to form galaxies. Third, globular clusters have significant abundances of heavy elements rather than primordial compositions. Self-enrichment is a possible solution although this is severely constrained by the narrow spread in the metallicities of the stars within most globular clusters. One must therefore postulate that all the low-mass stars observed today formed after the proto-clusters were enriched by high-mass stars. Another problem is that the metallicities of globular clusters are correlated with their positions, which is hard to understand if they formed before the collapse of proto-galaxies.

4. SECONDARY FORMATION

The idea that globular clusters formed during the collapse of proto-galaxies has been advocated by many authors. One argument in favor of secondary formation, mainly emphasized by observers, is based on the overall similarity between globular clusters and field stars in the spheroidal components of galaxies (see, for example, Searle 1977 and Searle and Zinn 1978). Such comparisons are most natural when restricted to the "halo" clusters (Zinn 1985). Another line of reasoning, which we emphasize here, is based on physical plausibility (Gunn 1980, McCrea 1982, Fall and Rees 1985). Our starting point is the widely held view that fragmentation and star formation should occur in a proto-galaxy when it can cool in a free-fall time (Binney 1977, Rees and Ostriker 1977, Silk 1977). This condition picks out a mass of order 10^{12} $M_{\odot}$ and a radius of order 10^{2} kpc. The cooling arguments have been extended to a picture in which the luminous components of galaxies form by the collapse of gas in dark halos that cluster hierarchically from small perturbations in the early universe (White and Rees 1978). The latest version of this story is the one with cold dark matter (Blumenthal, Faber, Primack and Rees 1984). Our theory for the origin of globular clusters is motivated in part by these ideas but the general features should apply in a much wider range of cosmological pictures.

For a proto-galaxy to collapse in free fall, the radiative cooling must remain at least as efficient as the gravitational heating. If the gas is lumpy, as expected in any realistic proto-galaxy, the overdense regions will cool more rapidly than the underdense regions. This process--a thermal instability--will produce a two-phase medium, i.e., cold dense clouds embedded in and confined by hot diffuse gas. Now there are two characteristic temperatures in the problem. One, the temperature of the hot gas, can be expressed as $T_h \approx (\mu_h/3k)\, V_{gal}^2$, where V_{gal} is a typical velocity for large-scale, gravitationally-induced motions and $\mu_h \approx 0.6\ m_p$ is the mean mass per particle of ionized gas. The other characteristic temperature, $T_c \approx 10^4$ K, is where hydrogen recombines and the cooling rate drops precipitously. We assume for the moment that the clouds do not cool to lower temperatures and justify this later. The densities of the two phases, once they reach pressure balance, are related by $\rho_c/\rho_h = (\mu_c/\mu_h)\ (T_h/T_c)$, where $\mu_c \approx 1.2\ m_p$ is the mean mass per particle of neutral gas. For $V_{gal} = 300$ km s^{-1}, a value appropriate to the Milky Way, we find $T_h \approx 2 \times 10^6$ K and therefore $\rho_c/\rho_h \approx 400$. Our detailed calculations show that this state is reached during the collapse of the proto-galaxy if the initial amplitudes of the perturbations giving rise to the clouds are of order 10%. Perturbations with larger amplitudes grow even more rapidly.

Any clouds with masses greater than some critical value will be gravitationally unstable and will collapse. The standard formula for an isothermal sphere confined by an external pressure p_h is

$$M_{crit} = 1.2(kT_c/\mu_c)^2\ G^{-3/2} p_h^{-1/2}. \tag{1}$$

This can be simplified by noting that the hot gas as a whole remains near the threshold for gravitational instability while it collapses. Combining (1) with a similar expression for a proto-galaxy of mass M_{gal} then gives

$$M_{crit} \approx \frac{1}{4}\ (T_c/T_h)^2\ f_h^{-1/2}\ M_{gal}, \tag{2}$$

where f_h is the fraction of the mass in the hot phase. In general, we expect f_h to be near unity when the first clouds form and to decrease thereafter. The exact value is not crucial, however, because f_h enters

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(2) only through a square root. Another way to estimate p_h and hence M_{crit} is by assuming that the cooling time of the hot gas is comparable to the free-fall time, as in the arguments that lead to a preferred scale for proto-galaxies. (This is what was done in our 1985 paper.) For $T_h \approx 2 \times 10^6$ K and $M_{gal} \approx 3 \times 10^{11}$ $M_\odot$, we find $M_{crit} \approx 2 \times 10^6$ $M_\odot$. This is somewhat higher than but reasonably close to the masses of globular clusters. Since T_h scales roughly as $M_{gal}^{1/2}$ (the Faber-Jackson and Tully-Fisher relations), the critical mass, as given by (2), should have little variation from one galaxy to another.

The clouds produced by a thermal instability can have a wide range of masses. In the absence of magnetic fields, thermal conduction sets a lower limit, which, unless the clouds are highly flattened or filamentary, is well below M_{crit}. If there is a tangled magnetic field with a strengh of only 10^{-15} G, conduction is suppressed and the lower limit on the masses is even smaller. Most of the clouds will therefore be gravitationally stable. They will persist in pressure balance with the hot gas until collisions produce agglomerations that are massive enough to collapse. We therefore expect the proto-clusters to have a narrow range of masses near M_{crit}. The value $M_{crit} \sim 10^6$ $M_\odot$ is, however, special only if the temperature of the cold gas "hangs up" at 10^4 K. A necessary condition for this to occur is that the cooling times of the clouds be comparable to or longer than their internal free-fall times so that they contract quasi-statically. If this condition were not satisfied, the gas would cool rapidly through 10^4 K and M_{crit} would be drastically reduced. Some of the smaller clouds might eventually reach temperatures low enough to become gravitationally unstable, but if the cooling time is large in comparison with the free-fall time, a feature near 10^6 $M_\odot$ will still be imprinted in the mass spectrum.

In gas with a primordial composition, the only significant cooling at temperatures just below 10^4 K is caused by molecular hydrogen. This would spoil our theory were it not that H_2 can be destroyed by radiation just longward of the Lyman limit (Stecher and Williams 1967). Even the hot gas in a proto-galaxy emits enough ultraviolet photons to keep molecular cooling at modest levels and this could be reduced further by radiation from massive stars or an active galactic nucleus. Once heavy elements are produced and dispersed within a proto-galaxy, they provide another source of cooling. In an idealized model with no heat input, we find that the temperatures of the clouds would remain near 10^4 K as long as the metallicity is less than or of order 10^{-2} $Z_\odot$. This estimate is in reasonable agreement with the abundance of heavy elements in many globular clusters. A completely realistic treatment would include heating mechanisms and might therefore be compatible with the higher metallicities of some clusters. There are several possibilities: (a) heating by supernovae, stellar winds, etc. within the proto-clusters, (b) photo-ionization by massive stars elsewhere in the proto-galaxy, (c) heating by cosmic rays, (d) photo-ionization by an active galactic nucleus. Any of these effects could raise the metallicity at which cooling becomes important but none of them can be calculated without additional assumptions.

A consequence of the previous arguments is that the first generation of stars would form in clouds with masses of order 10^6 $M_\odot$.

As the proto-galaxy is progressively enriched in heavy elements, cooling becomes more important and clouds with smaller masses can collapse. These objects would be more susceptible to disruption (they would lie outside the survival triangle) and the stars that formed in them would be released into a field population. The metallicity at which the transition occurs is a little vague because of the uncertainties in the heating mechanisms and the possibility of some self-enrichment in the proto-clusters. Moreover, some of the field stars with very low metallicities may have formed in globular clusters that were later disrupted. Nevertheless, we do expect the field stars, on average, to be slightly younger and to have higher metallicities than the globular clusters. The field stars, by forming later in the collapse of a proto-galaxy, should also have a space distribution more centrally concentrated than that of the globular clusters. As the result of various selection biases, these suggestions are not easy to test for the Milky Way but they are consistent with the available data for other galaxies (Forte, Strom and Strom 1981, Harris 1986, Mould 1986, Mould, Oke and Nemec 1986).

Gunn (1980) and McCrea (1982) pointed out that globular clusters might form in the compressed gas behind strong shocks in proto-galaxies. This could be especially important in collisions between sub-galactic fragments. To show the connection with our work, we consider two streams or fragments, each with a density ρ_o, that collide supersonically with a velocity V_{rel}. The resulting shocks propagate away from the center of mass with a velocity $V_{rel}/6$, leaving the layer of hot gas between them at rest. Just behind the shocks, the density and temperature are $\rho_h = 4\ \rho_o$ and $T_h = (\mu_h/12k)\ V_{rel}^2$. After a cooling time, a layer of cold gas forms, sandwiched between two layers of hot gas. Since, to a good approximation, all the gas between the shocks is isobaric, the densities and temperatures of the two phases are related by $\rho_c/\rho_h \approx (\mu_c/\mu_h)(T_h/T_c)$. The critical mass for gravitational instability is given by an expression that differs from (1) only in numerical factors of order unity. If the density of the fragments ρ_o is comparable to the mean density within the proto-galaxy, (2) should also be a valid approximation. For $V_{rel} \approx 2\ V_{gal}$ and $T_c \approx 10^4$ K, we obtain roughly the same result as before, $M_{crit} \sim 10^6\ M_\odot$. Thus, as regards the formation of globular clusters, it probably makes little difference whether the two-phase medium is produced by shocks or by a thermal instability. What is crucial is that the gas not cool to temperatures much below 10^4 K.

5. TERTIARY FORMATION

There are several ways in which globular clusters might form after the collapse of proto-galaxies. One suggestion is based on the fact that the central members of some clusters of galaxies with X-ray cooling flows have unusually large populations of globular clusters (Fabian, Nulsen and Canizares 1984). M87, at the center of the Virgo cluster, provides an interesting example. The pressure in the hot gas, which can be inferred directly from X-ray observations, is $p_h \approx 1 \times 10^{-9}$ $(R/\mathrm{kpc})^{-1}$ dyne cm^{-2} over the radial range 1 kpc $\lesssim R \lesssim$ 30 kpc (Stewart, Canizares, Fabian and Nulsen 1984). Furthermore, the optical filaments indicate that some of the gas is relatively cold, with a temperature near 10^4 K, and may be the result of a thermal instability. Under these conditions, the critical mass, $M_{crit} \approx 4 \times 10^5 \ (R/\mathrm{kpc})^{1/2} \ M_\odot$,given by (1) is comparable to the masses of globular clusters. However, since the metallicity of the gas is nearly solar and since there are no strong sources of heat, any clouds can cool through 10^4 K in a time of order 10^{-2} of their internal free-fall times (Fall 1986). Thus, a characteristic mass of order $10^6 \ M_\odot$ cannot have been imprinted in the recent past. The globular clusters must have formed when the metallicity was much lower or the heating rate much higher, perhaps at the time M87 itself formed. These arguments are consistent with some recent spectroscopic observations, which show that the metallicities of the globular clusters in M87 are similar to those of the globular clusters in the Milky Way (Mould, Oke, and Nemec 1986).

In another version of the tertiary hypothesis, globular clusters are assumed to form in disks and those now in spheroids are assumed to have got there by the merging of smaller galaxies or proto-galaxies (Rogers and Paltoglou 1984, Larson 1986). This is motivated in part by Zinn's (1985) observation that the globular clusters in our galaxy more metal rich than [Fe/H] $\approx$ -0.8 have the kinematics and space distribution of a thick disk. Moreover, the Magellanic Clouds and other late-type galaxies have many rich clusters of young and intermediate ages associated with the disk populations (Freeman, Illingworth and Oemler 1983). Although these objects are often referred to as globular clusters, they have many properties in common with the open clusters in the Milky Way, including a luminosity function with no preferred scale (Elson and Fall 1985a, b). When galaxies merge, they could hardly avoid adding clusters to a spheroidal component. However, if this process was ever important in our galaxy, it must have ended fairly early (within a few x 10^9 yr) because all the halo clusters appear to be old. The distinction between secondary and tertiary formation then becomes very blurred and some of the arguments about colliding fragments may apply.

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DISCUSSION

GNEDIN: My question concerns the cooling mechanism. You consider thermal bremsstrahlung only. What about a magnetic field? I believe it is very important for the cooling process.

REES: I don't think the magnetic field is important for cooling by a thermal plasma. However, even a weak field affects the conductivity, and thereby determines the minimum size of cool clouds embedded in a hot medium, as well as their likely shapes (sheets? filaments? etc.)

OSTRIKER: Martin, if I understand the Fall-Rees picture, it would predict a definite relation between the characteristic mass (at the peak of the luminosity function) of globular clusters and the mass of the parent galaxy (perhaps $M_{cl} \propto M^{1/2}_{gal}$). How well does the predicted relation accord with observation?

REES: Idealized versions of the model do indeed predict a slow dependence of cluster mass on galaxy mass - and indeed on galactocentric distance within a given galaxy. However I don't think too much should be made of these, because the efficiency of star formation and mass retention within each forming cluster is likely to depend on environment (e.g. external pressure).

PRYOR: Globular clusters in Zinn's disk look very similar to clusters in the halo. Could you comment on how this similarity arises in your model?

REES: Disk clusters probably formed in a qualitatively similar fashion to the halo clusters. The young "globular clusters" in, for instance, the LMC may not, however, form pressure-confined clouds in the same way.

COHEN: It appears that dark matter may not be necessary to stabilize the disk of the Milky Way and that there may not be a missing mass problem locally. Could you tell us your views on dark matter, particularly non-baryonic dark matter?

REES: There seems little doubt that there some kind of dark matter exists in halos and in clusters of galaxies. I'm personally agnostic about whether this is baryonic or not - but it's impressive how well the so-called "cold dark matter" cosmology has stood up to two or three years of intense scrutiny. As far as globular clusters are concerned, there is no firm evidence that they contain dark matter. However if the CDM cosmology is correct <u>and</u> globular clusters are pregalactic, then they would be surrounded by non-baryonic mini-halos.

ZINNECKER: May I inject a word of caution about your cooling curve below $T \sim 10^4$. I believe molecular hydrogen cooling is likely to be more efficient than calculated in the Fall and Rees (1985) Ap. J. paper

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which would pose a threat to your globular cluster formation theory. In this paper, you do not consider all the channels for H_2-formation (for example, the route via H^+_2 is not included). Moreover, H_2-formation is a tricky business involving non-equilibrium ionization, non-LTE level population, shielding etc. I wonder whether you could comment on these points?

REES: I agree that the thermal history of the 10^4 K clouds is important, because non-equilibrium processes are involved. However, a sufficiently intense UV background can unquestionably prevent H_2 formation - the most detailed calculations so far being those of Kang and Shapiro - though it is unclear how plausible it is that a protogalaxy generates this background at the appropriate stage.

OZERNOY: Martin, could you describe within the framework of your scheme, as a particular example, the differences in possible evolutionary ways of globular cluster formation in our Galaxy as compared with that in the Magellanic Clouds.

REES: I'm honestly quite unclear whether the Magellanic Cloud clusters are the same kind of beast at all. The work of Elson and Fall suggests that they formed continuously over the entire lifetime of the LM. Moreover, their mass function extends down to low values more typical of open clusters. (This is, unmistakably, a constraint on theories which attribute the globular clusters in our Galaxy to mergers with small disks.)

WEBBINK: Is there any difficulty posed to either the primordial or secondary scenarios for cluster formation in importing sufficient angular momentum to the condensing globular cluster to avoid strongly radial orbits and destruction by the galactic tidal field?

REES: Protogalaxies probably acquired their overall angular momentum via tidal torques. Gas that starts off at ~ 100 kpc would typically acquire the angular momentum appropriate to an orbit with perigalacticon at ~10 kpc. Of course the orbits of individual clusters would, in the Fall-Rees model, be influenced by random motions in the protogalactic gas. A better-developed theory than we yet have should be able to say something about the distribution of orbital eccentricities and hence tidal effects.

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