Globular Cluster Formation

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Abstract. The discovery of young globular clusters in merging galaxies and other environments provides an opportunity to study directly the process of globular cluster formation. Empirically it appears that globular cluster formation occurs preferentially in regions in which star formation occurs at a high rate and efficiency. Further, the interstellar medium in such regions is likely to be at a higher pressure than less active star-forming environments. An additional observational clue to the globular cluster formation process is that young globular clusters have little or no mass-radius relationship. In this paper I argue that high pressure and high star-formation efficiency are responsible for current globular cluster formation. I suggest that the precursors to globular clusters are molecular clouds and that the mass-radius relationship exhibited by such clouds is wiped out by a variable star formation efficiency.

1 Empirical Foundations

Early models of globular cluster formation were largely motivated by two observational results: Milky Way globular clusters are old and massive. Consequently, these models tended to exploit physical conditions unique to the early universe that might give rise to bound clusters of stars with masses around $10^5 M_\odot$. Over the last decade or so, observations of extragalactic globular cluster systems and the discovery of young globular clusters have dramatically expanded the empirical basis of globular cluster formation theories. Perhaps most importantly, young globular cluster systems allow the formation process to be probed directly. In this section I describe the observations that are useful in investigating and constraining the process of globular cluster formation.

1.1 What do we know?

The Milky Way globular cluster system is comprised of at least two distinct populations (e.g. Armandroff and Zinn 1988 and references therein). The more numerous metal-poor clusters are distributed in a spherical halo, whereas the metal-rich clusters have spatial and kinematic properties similar to the bulge or thick disk. Despite the marked distinction in these properties between the two populations, the mass distributions of the metal-poor and metal-rich clusters are indistinguishable. Other spiral galaxies also show evidence for similar metal-rich and metal-poor populations of globular clusters, the most compelling case being M31 (Ashman and Bird 1993; Barmby et al 2001; Perrett et al 2002).
A similar metallicity dichotomy is now well-established in the globular cluster systems of many elliptical galaxies (e.g., Kundu and Whitmore 2001; Larsen et al 2001). In the vast majority of cases, there are also clear spatial distinctions between the populations with the metal-rich clusters being more centrally concentrated than the metal-poor ones. There are currently only a handful of detailed kinematic studies of these systems (Zepf, these proceedings). In at least some of these studies, kinematic differences between the two globular cluster populations have been demonstrated. As in the case of spirals, the mass distributions of the two populations of globular clusters within an elliptical are indistinguishable. Further, the mass distributions of globular clusters in different galaxies are similar.

Perhaps the most important development in understanding globular cluster formation was the discovery of young globular clusters in currently merging galaxies (e.g., the reviews of Schweizer 1998; Ashman and Zepf 1998). As discussed further below, this allows the formation process to be studied directly rather than relying on extrapolations based on observations of ancient globular clusters. More generally, this discovery demonstrated that globular cluster formation is not a process that is dependent on conditions unique to high redshifts.

The recent discovery of intermediate-aged globular clusters in a handful of youngish ellipticals (see Goudfrooij in these proceedings and references therein) provides a useful link between ancient globular clusters and the very young objects in ongoing mergers. Of considerable interest is the finding that the age of these intermediate systems are consistent with the age of merger signatures in their host ellipticals. This provides additional support to the idea that globular cluster formation is not a uniquely cosmological phenomenon.

1.2 What does it all mean?

One of the traditional arguments against a pregalactic origin for globular clusters was the presence of color (interpreted as metallicity) gradients in the globular cluster systems of elliptical galaxies (Harris 1991). Clearly a pregalactic origin is hard to reconcile with such an observation since it requires higher metallicity clusters to preferentially adopt smaller galactocentric distances. However, the finding that these color gradients are the result of two populations of globular clusters with different spatial concentrations complicates this conclusion. Since there is currently no definitive evidence for color gradients within the individual populations, it is possible that one of the populations formed pregalactically, later becoming associated with the parent galaxy through hierarchical clustering. Equally, it is hard to avoid the conclusion that at least one of the globular cluster populations of elliptical galaxies must have formed within the galaxy itself. Again, if both populations were pregalactic there is no obvious mechanism for generating the spatial (and kinematic) differences between the two populations. Similar comments apply to the metal-poor and metal-rich globular cluster systems of the Milky Way and other spiral galaxies.

In order to explore this idea further, it is helpful to examine current ideas on the formation of globular cluster systems. The presence of metallicity bimodal-
ity in the globular cluster systems of ellipticals was predicted in the context of the merger model (Ashman and Zepf 1992; see also Zepf and Ashman 1993). The metal-poor globular clusters are identified as those originally in the halos of progenitor spirals, whereas the metal-rich ones are assumed to form in the spiral-spiral merger that formed the elliptical. Thus in this picture, the metal-rich clusters form with the elliptical, whereas the metal-poor ones could have a pregalactic origin. In the dissipationless hierarchical clustering scenario of Côté et al (1998, 2002), metallicity bimodality is attributed to the clustering of a large number of galaxies and their associated globular cluster systems. The metal-poor clusters are those associated with numerous dwarf galaxies, whereas the metal-rich ones formed around the largest “seed” galaxy. Finally, in the multiphase collapse model of Forbes et al (1997), both populations of globular clusters form \textit{in situ} within a collapsing elliptical, with the metal-poor globular clusters forming first and the metal-rich ones being produced in a secondary burst of star formation.

This discussion illustrates that in all extant models of globular cluster system formation at least some globular clusters are formed within galaxies. Indeed, in all cases, the metal-rich clusters are associated with a significant star formation event in the parent galaxy. Based on the observations outlined above, this general result seems hard to dispute. Beasley et al (2002) have recently studied this issue using a semi-analytic approach. They find consistency with observation in schemes where metal-poor clusters form before massive galaxies and metal-rich ones form in star-forming events associated with massive galaxies such as mergers. The presence of young and intermediate-aged globular clusters in mergers and merger remnants indicates that globular clusters \textit{can} form in mergers, but does not necessarily require that all globular clusters form in such environments. Indeed, the globular cluster systems of dwarf galaxies clearly did not form in major mergers. I will return to these systems in Section 3.

2 Globular cluster formation in mergers

While not all globular clusters form in major mergers, the fact that some do gives us an excellent starting point for investigating the globular cluster formation process. This approach is made more attractive by the evidence that globular cluster formation is rare in other star-forming regions such as the disks of normal spirals. Larsen in these proceedings discusses “young massive clusters” in normal spiral disks. Whether these objects are analogs of young globular clusters or whether they are more diffuse objects is yet to be determined, but the critical issue is that globular cluster formation is clearly more prevalent in regions where the star formation rate is high such as merger-induced starbursts.

2.1 The importance of pressure

As noted by several authors (e.g., Elmegreen and Efremov 1997), the mass function of Giant Molecular Clouds (GMCs) in the Milky Way and other nearby
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galaxies and young globular clusters have similar slopes when parameterized as power laws. Further, the slope of the mass function is also consistent with that of old globular clusters at the high-mass end of the distribution (e.g., Harris and Pudritz 1994).

There are two (possibly related) reasons why such GMCs do not produce a population of young globular clusters in the Milky Way and similar environments. First, the star formation efficiency in such GMCs is low. Consequently, the typical mass of star clusters formed in these clouds is less than that of young globular clusters. In fact, since the mass distribution is well-approximated by a power law, high-mass clusters will still form from ordinary GMCs provided one has a sufficient number of such clouds in a given galaxy. However, if such massive clusters do form, they will not resemble globular clusters. This is because the radii of GMCs in normal star-forming environments are much greater than the characteristic radii of globular clusters.

One of the notable differences between the interstellar medium (ISM) in quiescent disks and starbursts is that the pressure in the latter is inferred to be much higher (e.g., Heckman et al 1993, 1990). The relevance to the formation of dense star clusters is immediately apparent. Clearly GMCs in a high-pressure environment will have higher densities and smaller radii than their counterparts in a galaxy like the Milky Way. This is one reason why high pressure has been suggested as a critical physical reason why globular clusters form in galaxy mergers (Elmegreen and Efremov 1997; Ashman and Zepf 2001).

To quantify this idea it is useful to employ the Ebert-Bonner relations (Ebert 1955; Bonner 1956; see also Harris and Pudritz 1994; McLaughlin and Pudritz 1996) for self-gravitating, pressure-bounded isothermal spheres:

\[ M_c = \frac{3.45 \sigma^4}{\gamma^{3/2} (G^4 P_s)^{1/2}} \]  
\[ r_c = \frac{0.69 \sigma^2}{\gamma^{1/2} (G P_s)^{1/2}} \]  

Here \( M_c \) and \( r_c \) refer to the mass and radius of the cloud, \( P_s \) is the cloud surface pressure, \( \gamma \) is a factor of order unity which is dependent on the nature of the equilibrium, \( \sigma \) is the one-dimensional velocity dispersion within the cloud, and \( G \) is the gravitational constant.

One can eliminate the velocity dispersion from these expressions to obtain a simple scaling relation:

\[ r_c \propto M_c^{1/2} P_s^{-1/4} \]  

If GMCs in the ISM of mergers are in equilibrium, the above relations and inferred pressures in mergers imply that GMCs with masses of order \( 10^5 \) \( M_\odot \) have radii consistent with those of young globular clusters. Along with the similarities in mass functions, this result suggests that GMCs in high-pressure environments are at least plausible progenitors to young globular clusters. At some level, this result is hardly surprising. Given that young globular clusters are found in merging galaxies, it is difficult to imagine any other progenitor than dense molecular
clouds. However, it is significant that quantitatively the densities of such clouds in high-pressure environments are consistent with the densities of young globular clusters.

It is important to add that there is little direct information about the properties of molecular clouds in these environments. It seems unlikely that globular cluster progenitors are simply those GMCs originally in the disks of the merging spirals. This is because the compression of such clouds when the surrounding warm ISM is shock-heated is likely to cause cloud fragmentation before high densities are reached (e.g., Jog and Solomon 1992; Jog and Das 1996). That is, the original GMCs of the spirals are unlikely to reach equilibrium with the high-pressure ISM before fragmentation. It seems more probable that globular cluster progenitor clouds form within the ISM of the merger once high pressures have been established.

2.2 The strange case of the mass-radius relationship

While the above considerations provide a simple framework for the formation of globular clusters in mergers, there is one oddity that must be explained if molecular clouds at high pressure are to be identified as globular cluster progenitors. This is the observation that GMCs, at least in normal star-forming regions, have a mass-radius relation consistent with the Ebert-Bonner relations given above [see equation (3)] whereas young globular clusters have a weak or non-existent relation between mass and radius (Ashman and Zepf 2001). These results have been established for GMCs in the Milky Way (see the summary of observations given by Harris and Pudritz 1994), as well as M33, the LMC and the SMC (Wilson and Scoville 1990; Johansson 1991; Rubio et al. 1993). For young globular clusters, observations of the galaxy merger NGC 3256 indicate that there may be a weak correlation between mass and radius (Zepf et al. 1999), but one that is clearly much shallower than the mass-radius relation of GMCs given in equation (3). A similar weak or absent correlation between mass and radius is well-established for the old globular clusters of the Milky Way (van den Bergh et al. 1991; Djorgovski and Meylan 1994; Ashman and Zepf 1998) and also seems to hold for the young star clusters in the LMC (van den Bergh 1991), and for young star clusters in the Galaxy (e.g. Testi, Palla and Natta 1999).

2.3 A variable star formation efficiency

Assuming that globular cluster progenitors are clouds in equilibrium, these observations require that the original mass-radius relationship of such clouds is wiped out during the globular cluster formation process. For this to occur it is apparent that either the mass or the radius (or both) of the final star clusters must differ from those of the original clouds. One promising mechanism for producing such an effect is that the star formation efficiency within clouds varies with mass and/or radius. Much of the following discussion of this possibility follows the study given in Ashman and Zepf (2001).
Let $\epsilon$ to be the star formation efficiency such that

$$\epsilon = \frac{M_*}{M_c}$$  \hspace{1cm} (4)

where $M_*$ is the mass of the star cluster resulting from a cloud mass $M_c$. To determine the mass-radius relation of clusters, it is clear that we also need to be able to calculate the final cluster radius, $r_*$, produced by a cloud with radius $r_c$. In general, recently formed clusters are expected to undergo a phase of expansion so that $r_* > r_c$. We assume that a cloud fragments and produces an initial cluster of radius $r_c$. If the gas loss is slow (i.e., it occurs on timescales longer than the cluster dynamical time) the product of mass and radius is an adiabatic invariant. Under these conditions, the final cluster radius is related to the star formation efficiency by:

$$\frac{r_*}{r_c} \simeq \epsilon^{-1}.$$  \hspace{1cm} (5)

(Hills 1980; Richstone and Potter 1982; Mathieu 1983). Thus lower star formation efficiencies lead to greater expansion with sufficiently low efficiencies producing unbound clusters. This expression has recently been verified numerically by Geyer and Burkert (2001) for the case of slow mass loss. For more rapid mass loss, these authors find larger expansion rates at a given $\epsilon$, but for $\epsilon < 0.4$ the clusters are unbound.

Ashman and Zepf (2001) investigated the consequences of a star formation efficiency scaling with some power of cloud binding energy per unit mass, $M_c/r_c$:

$$\epsilon \propto \left(\frac{M_*}{r_c}\right)^n$$  \hspace{1cm} (6)

Using equations (3) through (6) and some algebra one obtains a mass-radius relation for the resulting clusters:

$$r_* \propto M_*^{(1-n)/(n+2)} P_s^{[1-2(n+1)]/[2(n+2)]}$$  \hspace{1cm} (7)

The weak or absent mass-radius correlation of globular clusters is reproduced if the exponent on $M_*$ in equation (7) is close to zero. This occurs when $n \simeq 1$. For the specific case of the young globular clusters in NGC 3256, Zepf et al (1999) found $r_* \propto M_*^{0.1 \pm 0.1}$ (assuming a constant cluster mass-to-light ratio) which is reproduced by $n \simeq 0.75 \pm 0.25$. The value $n = 1$ is interesting since it corresponds to the case of a star formation efficiency which is directly proportional to the binding energy per unit mass of the precursor gas clouds. An increase in star formation efficiency with velocity dispersion (which scales as the square root of binding energy per unit mass, $n = 0.5$) has been suggested by Elmegreen et al (1993) and Elmegreen and Efremov (1997).

Throughout the above discussion it has been assumed that globular clusters form from clouds in equilibrium, since it is this equilibrium that leads to the cloud mass-radius relationship. It is important to note that there is currently little information about the nature of molecular clouds in the ISM of merging
Galaxies. There have been suggestions that the progenitor clouds to globular clusters may not be in equilibrium prior to fragmentation (see McLaughlin in these proceedings and references therein). As far as I am aware, the implications for the mass-radius relation of the resulting clusters have not been investigated.

2.4 Constraints on star formation efficiency variations

One important aspect of this discussion is that independent considerations place stringent constraints on variations in star formation efficiency. This is because of the similarity of the mass function slopes of GMCs and young globular clusters. Any star formation efficiency that includes a dependence on mass will inevitably produce a cluster mass function with a different slope to that of the progenitor clouds. To quantify this, consider the usual parameterization of the mass spectrum of clouds and clusters:

\[ N(M_c) dM_c \propto M_c^{-\beta} dM_c. \]  
\[ N(M_\ast) dM_\ast \propto M_\ast^{-\alpha} dM_\ast, \]  

These quantities can be related through the expression

\[ N(M_\ast) dM_\ast \propto N(M_c) \left( \frac{dM_c}{dM_\ast} \right) dM_\ast. \]  

Ashman and Zepf (2001) showed that for a star formation efficiency given by equation (6) this last expression implies a relation between the cloud and cluster mass function slopes:

\[ \alpha = \frac{2\beta + n}{n + 2}. \]  

Since \( \alpha \) and \( \beta \) are found observationally to be comparable, it is apparent that the value of \( n \) is constrained to be small. If, as argued by Elmegreen and Falgarone (1996), \( \beta = 2 \), then a typical observational value of \( \alpha \) of 1.8 implies \( n = 0.5 \). Using these same values and the weak mass-radius relation for young globular clusters in NGC 3256 leads to marginal consistency with \( n = 1 \).

Note that in general this picture predicts that \( \alpha < \beta \). Thus determinations of the mass distributions of clouds and clusters have the potential to refute or support this scenario. Unfortunately, the current uncertainties in these quantities, as well as the fact that cluster and cloud mass spectra are rarely derived for the same systems, do not allow a definitive test of the scenario as yet. Future observations of the mass functions of molecular clouds and globular clusters in the same system will address this question. For example, ALMA will have the angular resolution and sensitivity to pin down the cloud mass spectrum in merging systems. Interestingly, a dependence of star formation efficiency to any positive power of cloud density, as is the case in Schmidt-type laws, can already be ruled out (Ashman and Zepf 2001).

One further potential constraint on a variable star formation efficiency is that for low enough values the resulting star clusters will be unbound. There
are several complicating factors in determining the mass-scale at which this occurs. For example, the center of a cloud might produce stars with a sufficiently high efficiency to form a bound cluster, but the global star formation efficiency (relevant to the arguments above) might be low. More generally, the lowest star formation efficiency that can produce a bound cluster is still a debated question. It is also worth noting that in the current picture it is the low-mass clusters that have the lowest star formation efficiencies and thus are most likely to be unbound. The dissolution of these clusters in this manner may be relevant to low-mass cluster destruction in general, which is required if the young globular cluster mass function is to evolve into that of old globular clusters (e.g., Fall and Rees 1977; Murali and Weinberg 1996; Gnedin and Ostriker 1997; Vesperini 1997 and in these proceedings).

2.5 The connection between pressure and star formation efficiency

A critical question in this discussion is why there might be a relationship between star formation efficiency and the surface pressure of molecular clouds. First, it is important to note that observationally the star formation efficiency in merger-induced starbursts is high. Several authors have attributed this high star formation efficiency to the high pressure in such environments (e.g., Jog and Solomon 1992; Jog and Das 1996; Elmegreen and Efremov 1997). It is exactly the high ambient pressure, of course, that produces clouds with a high binding energy.

More generally, there are plausible reasons why star formation efficiency might depend on the binding energy per unit mass of clouds (see also Elmegreen et al 1993; Elmegreen and Efremov 1997). To a first approximation, the disruptive energy input from massive stars will be proportional to the number of such stars and thus the mass of the cloud, hence the normalization of binding energy to unit mass. It seems likely that clouds with a higher binding energy will be less affected by such disruption and therefore convert a higher fraction of their gas mass into stars. It is important to distinguish in this context between global and local effects. Clearly binding energy considerations are central to establishing whether a young cluster will remain bound at all. In terms of a rationale for a star formation efficiency dependent on binding energy, the issue is that local feedback effects are likely to be more important (and therefore more likely to suppress further star formation) in clouds of higher binding energy.

2.6 More on cloud fragmentation

In the above discussion no attempt has been made to address the details of the cloud fragmentation process. Further, the Ebert-Bonner relations that underpin the scaling arguments refer to the mean properties of clouds. Consequently, the potentially important issue of the density profiles of clouds is not addressed in the above approach. It seems inevitable that any understanding of fragmentation must include a study of how fragmentation and subsequent feedback processes occur locally within clouds, and thus on the density profile of clouds. Many of
these issues are discussed in the comprehensive review by Elmegreen (2002; see also McLaughlin in these proceedings).

Of possible relevance to the elimination of the mass-radius relationship is the fact that fragmentation is dependent on the equation of state of the cloud (see, for example, Li in these proceedings). This can be understood using standard Jeans mass arguments. If the equation of state is expressed using the usual polytropic form:

\[ P \propto \rho^\gamma \]  

it follows that the Jeans mass can be written

\[ M_J \propto \rho^{3/2(\gamma-4/3)} \]  

One expects fragmentation to proceed if cloud contraction, and thus an increase in cloud density, leads to a decrease in the Jeans mass. Clearly this occurs when \( \gamma < 4/3 \).

Simulations by Li (these proceedings; see also Spaans and Silk 2000 and references therein) support this expectation.

Of interest in this context is the fact that the critical value of \( \gamma = 4/3 \) also corresponds to clouds with no mass-radius relationship. This is because such a value implies that cloud mass is independent of density, as is apparent from equation (13). If the progenitor clouds of globular clusters initially have \( \gamma > 4/3 \) with this value subsequently decreasing, it is possible that fragmentation begins once the value of 4/3 is reached. Consequently, the resulting clusters would likely have no mass-radius relationship. The critical issue is therefore whether molecular clouds in starburst environments are likely to experience this kind of evolution. Unfortunately, there is currently no clear consensus on the equation of state of molecular clouds and related stability issues even in systems where these objects are well studied (e.g., McLaughlin and Pudritz 1996; McKee and Holliman 1999; Curry and McKee 2000 and references therein).

Despite this uncertainty, there are general considerations that suggest molecular clouds in starbursts may be initially characterized by large values of \( \gamma \) (assuming a single polytropic index is adequate at all; see Curry and McKee 2000). As argued earlier, clouds that produce globular clusters in such environments probably formed after the initial shock-heating of the ISM, since pre-existing clouds would fragment before reaching the densities typical of globular clusters. Consequently, the progenitor clouds will be in an environment with a significant radiation field. The resulting heating of clouds will tend to push \( \gamma \) to large values. Spaans and Silk (2000) have investigated this issue and note that opaque dust in starbursts is an additional factor that tends to lead to large values of \( \gamma \). These authors also find that \( \gamma \) subsequently decreases towards unity in such environments. It therefore seems at least plausible that there is a physical connection between the critical value of \( \gamma \) required for cloud fragmentation and the absence of a mass-radius relation in globular clusters.
3 The origin of metal-poor clusters

While there is compelling evidence that metal-rich globular clusters formed during major star-forming events within their parent galaxies, the origin of metal-poor clusters is less clear. Empirically, metal-poor clusters are found in a wide range of environments from the faintest dwarfs to the halos of massive spirals and ellipticals. This ubiquity suggests that the metal-poor globular clusters may have a pregalactic origin. However, it seems unlikely that such globular clusters represent the first bound structures to form in the universe, as originally envisaged by Peebles and Dicke (1968). The well-known problem is that such cosmological structures are expected to be surrounded by dark matter halos, whereas observations of metal-poor globular clusters in the Milky Way rule out the presence of such halos (e.g., Moore 1996).

One interesting possibility for resurrecting a pregalactic origin has recently been proposed by Bromm and Clarke (2002). These authors have carried out numerical simulations of structure formation within dwarf galaxies at early epochs. They suggest that gas in dark matter “subhalos” within such dwarfs fragments to form the stellar component of globular clusters and that subsequent violent relaxation of the dwarf galaxy itself wipes out the individual subhalos around the globular clusters. The mass of globular clusters in this picture is thus effectively set by the mass of the subhalos and the ratio of gas to dark matter. This differs from the original Peebles and Dicke (1968) scenario in the sense that globular cluster formation occurs within a larger bound system, but it does connect at least some globular cluster formation with cosmological conditions through the dark matter mass spectrum.

To some extent, the picture of Bromm and Clarke (2002) is similar to other ideas in which the sites of metal-poor globular clusters are larger objects with masses around $10^8 M_\odot$. There are several motivations for such a view. For instance, there is evidence that the halo of the Milky Way was assembled from “Searle-Zinn” sub-galactic fragments (e.g., Searle and Zinn 1978). Further, such a picture is consistent with successful models of the formation of cosmological structure. Current dwarf galaxies may be the surviving remnants of such objects (see, however, the caveats presented by Santos in these proceedings). Hierarchical clustering of some of these fragments into larger galaxies leads to metal-poor globular clusters in the halos of spirals and ellipticals. Along similar lines, Harris and Pudritz (1994; also McLaughlin and Pudritz 1996) presented a globular cluster formation model in which the sites of formation are “Super Giant Molecular Clouds” (SGMCs). While it may be difficult to produce such massive clouds in current galaxy mergers (e.g., Ashman and Zepf 1998), such SGMCs are similar to the Searle-Zinn fragments discussed above.

In Section 2 I argued that high pressure is a necessary condition for globular cluster formation. It is therefore of some interest to establish whether high-pressure conditions might have existed in sub-galactic fragments at earlier epochs. Steve Zepf and I are currently investigating this question. Our preliminary results suggest that high pressure conditions can be achieved in such systems through feedback processes associated with massive stars. However, the
shallow potential wells of these systems mean that the gas is unlikely to remain bound to the fragments for long (see also Dekel and Silk 1986). The implications for globular cluster formation are currently being investigated.

A critical observational issue at the center of understanding the formation of metal-poor clusters is the uniformity of the metallicity of these objects. If all metal-poor globular cluster systems have similar mean metallicities, it suggests that all metal-poor clusters formed in similar environments. In this case, pregalactic formation in sub-galactic fragments is an attractive possibility (e.g., Ashman and Zepf 1992; Ashman and Bird 1993). Some variation in mean metallicity would not rule out this option provided it did not correlate with properties of the current parent galaxy. This is because there is evidence that the mean metallicity of the globular cluster systems of dwarf galaxies increases with galaxy luminosity (e.g., Lotz, these proceedings and references therein).

4 Conclusions

While there are still many aspects of globular cluster formation that are poorly understood, there does appear to have been significant progress over the last few years. Specifically, the discovery of young globular clusters in ongoing mergers has provided an empirical basis to the study of globular cluster formation. One notable result is that there is no longer any need to invoke conditions unique to the early universe in order to explain the origin of these objects. Indeed, the approach to understanding globular cluster formation advocated in this paper is to first understand why globular clusters form in such abundance in regions where the star-formation rate is high.

The realization that globular cluster formation is not a process unique to the early universe has also made globular clusters themselves less unique. Current evidence is consistent with the view that all star clusters are fundamentally similar and that globular clusters represent one end of the star cluster spectrum. This view is reinforced by the finding that both open and globular clusters share the curious weak or absent correlation between mass and radius. While this state of affairs may produce some semantic issues, such as how to define a globular cluster, it also offers the exciting possibility of a unified approach to the formation of all star clusters.

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