The Formation and Evolution of Star Cluster Systems
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EXECUTIVE SUMMARY

Star formation plays a central role in the evolution of galaxies and of the Universe as a whole. All star-forming regions contain star clusters, and thus building a coherent picture of how clusters form and evolve is critical to our overall understanding of the star formation process. Most clusters disrupt after they form and in doing so contribute to the field star populaton, but some of the massive and dense clusters remain bound and survive for a Hubble time. These globular clusters then provide valuable observational probes of the formation history of their host galaxies. In particular, the age and metallicity can be determined for each globular cluster individually, allowing the distribution of ages and metallicities within a galaxy population to be constrained. Globular clusters are also important kinematical probes of the outer halos of galaxies, and because of their very old age, provide an observable window into the earliest epochs of galaxy and structure formation.

The growing realization that the study of star clusters has direct relevance for the question of how galaxies evolve has placed this field into the forefront of astrophysical research in recent years. We believe that we are on the verge of answering a number of fundamental questions in the next decade which will significantly impact our understanding of the formation, assembly, and evolution of galaxies, and will provide important details on the process of star formation itself. Already-planned and upcoming facilities and capabilities (e.g., WFC3 on HST, ALMA, wide-field ground-based facilities, computational advances) will drive new discoveries in this area. However, we identify three issues for the Decadal survey that are critical for enabling significant future breakthroughs. These are:

(1) Effective access for the general observer community to a range of current and near-term facilities like HST, ALMA, and ground-based 4m and 8m-class telescopes.

(2) The inclusion of General Astrophysics programs in future missions like JWST, JDEM, TMT, and ATLAS.

(3) Flexible funding structures that support multi-wavelength, multi-facility, interdisciplinary research, including funding for the theoretical work that is key to understanding and interpreting the observations.

1. Background

The spectacular HST images of the starbursting galaxy NGC 1275 (Holtzman et al. 1992) revealed a populous system of compact and massive young star clusters, with all the properties expected of young globular clusters. Subsequent observations found populations of similar massive, dense star clusters in many systems, from the nearby merging "Antennae" galaxies shown in Figure 1 (Whitmore & Schweizer 1995) to many other star-forming galaxies (e.g. Larsen & Richtler 1999), showing that the formation of these compact, massive clusters occurs wherever there is vigorous star formation. While these and many other observations clearly show where and when dense star clusters form, *how* they form is still very much an open question.

One key window into the formation and evolution of star cluster systems is their mass function. For young cluster systems, the mass function can be approximated as a power law, $\psi(M) \propto M^{\beta}$, with $\beta \approx -2$ (e.g. Zhang & Fall 1999, Bik et al. 2003). However, the "universality" of this form in different environments and among different galaxies is uncertain

Figure 1: A multiband HST image of the "Antennae," showing a rich population of young clusters and many other features associated with these merging galaxies. The clusters are seen here as bright, compact dots, and the more luminous of these objects have masses inferred from photometry and confirmed with spectroscopy that are similar in mass to Galactic globular clusters.

and remains to be determined (e.g. Larsen 2009, Whitmore, Chandar, & Fall 2007, Gieles et al. 2006). Furthermore, star clusters begin to evolve dynamically as soon as they are formed, with stars from disrupted clusters building up the field star populations in galaxies. Dynamical evolution most likely explains the stark difference between the cluster mass functions in young systems compared to old systems like M87 and the Galaxy (Figure 2). However, the current literature contains many different observational conclusions and theoretical models for this transition. Distinguishing between these various ideas has important implications for a number of questions, such as the role of feedback within forming clusters and the relationship between stars in clusters and in the field.

Since clusters form during major star formation episodes, they provide a valuable fossil record of the assembly history of their host galaxies. One key discovery in this fossil record is that the metallicity distributions of the globular cluster systems of elliptical galaxies are typically bimodal (e.g. Kundu & Whitmore 2001, Larsen et al. 2001, Peng et al. 2006). Detailed follow-up of these results (which are based on HST studies in optical colors) has been done using both ground-based optical spectroscopy with large telescopes (e.g. Strader et al. 2007) and near-infrared photometry (Kundu & Zepf 2007). Furthermore, extensions from the centers of the galaxies studied with the modest field of view of HST to the much larger extent of the total globular cluster system have been carried out in several cases (e.g., Rhode & Zepf 2004).

In broad terms, the metal-rich globular cluster population is similar in color, metallicity, radial distribution, and kinematics to the bulk of the stellar population in early-type galaxies. The spatially extended, metal-poor globular cluster population is then associated

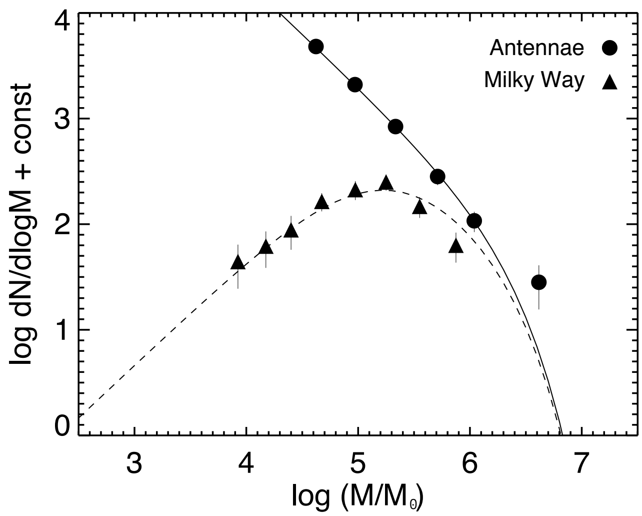

Figure 2: A plot comparing the mass function of the young star cluster system of the Antennae from Fall, Chandar, & Whitmore (2009) to that of the globular cluster mass function in the Milky Way. This plot shows the stark difference between these mass functions, indicative of strong dynamical evolution.

with an early formation epoch in the galaxy's history. However, exactly how and when these globular cluster populations were formed is a key unanswered question. Although bimodality was predicted by Ashman & Zepf (1992) and accounted for in other proposed formation scenarios (Forbes, Brodie & Grillmair 1997, Côté, Marzke, & West 1998), detailed models using the current generation of semi-analytic codes or hydrodynamical simulations do not naturally produce bimodality in the cluster metallicity distributions (e.g., Beasley et al. 2002, Kravstov & Gnedin 2005). A number of possibilities have been proposed, including associating the metal-poor population with clusters that formed before reionization (e.g. Santos 2003, Rhode, Zepf, & Santos 2005) but this remains to be tested on both observational and theoretical grounds. Thus, the origin of one of the most basic observational properties of globular cluster systems is very much an open question, with a number of proposed avenues for future advances that will shed light on both globular cluster and galaxy formation.

2. Central Science Questions

Here we identify three fundamental questions about star clusters and their host galaxies, and describe the upcoming advances that can help answer them. While it is easy to imagine major progress on all three of these questions in the coming decade, it is the unexpected surprises, generally driven by new observational capabilities, that are likely to drive the field in the longer term. **This highlights the need for effective access to a wide array of observational facilities for the general astronomical community.**

1. What physical conditions lead to the formation of massive, dense star clusters?

Observations have established that massive, dense star clusters form in regions of vigorous star formation. The next step is to gain a better physical understanding of how this happens. We anticipate that ALMA will provide key results on the structure of molecular gas in starbursting regions. These include establishing whether or not compact massive clouds exist in these regions, what fraction of the gas mass is in dense clumps, and how the mass function of molecular clouds compares with that of recently formed clusters. Multi-

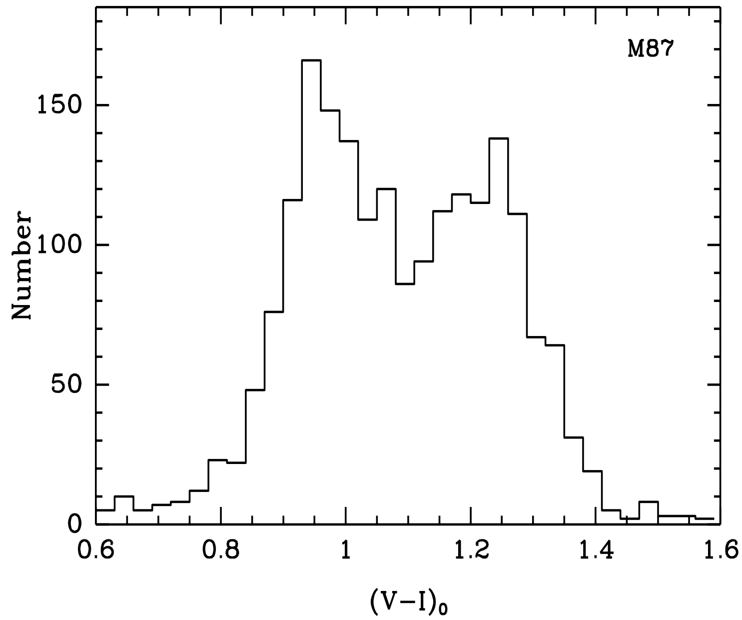

Figure 3: A plot of color vs. magnitude for the globular clusters in the Virgo giant elliptical galaxy M87, from Kundu & Whitmore (2001) with additional new outer radii pointings included. This clearly shows the metal-rich (red) and metal-poor (blue) populations that are typical of elliptical galaxies. These subpopulations of metal-poor and metal-rich globular clusters have been confirmed with near-infrared photometry and optical spectroscopy and are often seen in giant galaxies (both spirals and ellipticals) in the local universe.

wavelength studies will also be critical, since measurements from the near UV through near IR are needed to determine the mass function of newly formed star clusters. In the near-term, this emphasizes the importance of WFC3 on HST, while on longer time scales several different capabilities will be important, including JWST and perhaps ground-based adaptive optics (AO). Spectroscopy in the infrared and optical is important for characterizing the physical conditions (such as temperature, density, and pressure) in the regions forming clusters. Theoretical advances will be motivated by future observations and by increases in computational capability. Current models of the formation of massive dense clusters are primarily descriptive, proposing, for example, that it is the high pressure of the interstellar medium in star-forming regions that leads to the formation of massive, dense star clusters (e.g. Elmegreen & Efremov 1997, Ashman & Zepf 2001), or appealing instead to gravitational instabilities (e.g. Escala & Larson 2008). An increase in computational capabilities will allow the current generation of N-body simulations, which focus on star clusters of relatively modest mass, to be scaled up to the higher masses of globular clusters.

2. What are the dominant physical processes that destroy star clusters?

Star clusters begin evolving dynamically as soon as they are formed. Understanding how they do so is central to many questions in the study of star clusters and their relation to galaxies. Disruption also governs how former cluster stars build up the field star population in galaxies. Observationally, constraints on early disruption processes come from cluster age distributions and mass functions. For example, the age distribution of clusters in several galaxies appears to decline starting at very young ages, suggesting that many clusters fall apart easily (e.g., Whitmore et al. 2007). It is not yet clear however, which mechanism is most responsible for this rapid destruction. Mass loss and the disruption of clusters over a Hubble time are also likely responsible for the very different shapes observed for young and ancient star cluster systems (Figure 2). However, these disruption processes must also account for the observation that the mass function of old globular clusters appears to be similar nearly everywhere. Several different scenarios have been proposed to explain this observation, each appealing to different destruction mechanisms that act on different time scales (e.g. Parmentier et al. 2008, Vesperini & Zepf 2003, McLaughlin & Fall 2008).

The most immediate way to address these questions with observations will be to use HST WFC3 to obtain high spatial resolution, multicolor photometry for star cluster systems that span a range of ages. In the future, JWST and ground-based AO will push the field much farther. The second key set of data for understanding dynamical evolution is accurate, deep cluster mass functions covering the full extent of the cluster system. This requires wide-field imaging with HST-like spatial resolution, a possible JDEM capability. On the theoretical front, one promising approach is to identify sites of globular cluster formation in cosmological simulations, and to follow the dynamical evolution of these sites. Although very challenging computationally, some glimpse into how this might work is given by the recent work of Prieto & Gnedin (2008).

3. What do globular clusters tell us about the formation of galaxies?

Bimodal metallicity distributions are observed in the globular cluster systems of most ellipticals (e.g. Kundu & Whitmore 2001, Larsen et al. 2001, Peng et al. 2006), as well as in spirals such as the Milky Way (Zinn 1985) and M31 (Perret et al. 2002). The metal-poor globular cluster populations may be associated with early, relatively chaotic halo formation, and the metal-rich populations with the bulk of the spheroidal/bulge component of the galaxy. One key discovery is that massive galaxies host larger numbers of metal-poor globular clusters (normalized by galaxy mass) (e.g., Rhode et al. 2007). Is this "biasing" a sign of an early, pre-reionization formation epoch for the metal-poor globular clusters and the massive galaxies that host them? Or does this correlation perhaps instead result from other processes, such as the dynamical evolution of globular cluster systems? Advances in this area will come from campaigns to establish total numbers as a function of cluster color and galaxy mass, morphology, and environment using ground-based imaging with wide ($\sim 1^{\circ}$) fields to cover the full extent of the globular cluster systems. Wide-field, sub-arcsecond-resolution imagers like the WIYN One Degree Imager, CFH12K, and Subaru Suprime-Cam will lead the field in the near term, with LSST being valuable in this area over the longer term.

A second key question here is, did all of the metal-rich globular clusters form at early epochs, or were a significant number formed more recently? Globular clusters are invaluable for identifying formation events of intermediate ages (e.g. $z < 1$) and those that involve only a modest fraction of a galaxy's total mass, because the metallicities and ages of globular clusters can be determined on an individual basis. This lifts many of the degeneracies between age, metallicity, and burst strength present in studies of integrated galaxy light. The two primary approaches for estimating ages and metallicities — optical spectroscopy and near-infrared to optical photometry — provide valuable cross-checks on one another (see, e.g., review by Brodie & Strader 2006). Optical spectroscopy has advanced dramatically with the availability of multi-slit spectrographs on 10-m class telescopes, and will leap forward again with planned 30-m class telescopes. The cluster radial velocities from this spectroscopy also provide useful kinematic probes of the outer halos of elliptical galaxies. High resolution, wide-field imaging in the infrared will improve dramatically with WFC3 and with JWST. Eventually wide-field, high spatial resolution optical and near-infrared imaging may be provided by JDEM. Theoretical work will also be crucial. Cosmological simulations can now resolve the structure of the ISM in galaxies down to tens of parsecs, which allows for tracing the formation of giant molecular clouds in galaxy disks. Based on the advances of the last decade, we can expect dramatic growth in the quality and quantity of simulations in the next ten years. The result will be more robust predictions for the amount and intensity of star cluster formation in galaxies of various masses and types throughout cosmic history, and for the mass, age, and metallicity distributions of globular cluster systems in particular. These predictions will need to be evaluated using modern observational data of comparable volume and accuracy, so advancements in theory and observations are highly linked.

3. Conclusions

Star clusters are at the nexus of several fields in astrophysics, and provide critical clues to the basic processes of star formation and galaxy evolution. We have identified three questions that are of central importance in star cluster research: (1) What physical conditions produce massive, dense star clusters? (2) What are the dominant physical processes that destroy star clusters? (3) What do globular clusters tell us about the formation of galaxies? **Answering these important physical questions will not require a specific mission or instrument in the next decade, but will instead depend on the broad availability of general purpose telescopes.** In order to support this growing research field, we recommend the following:

- General observer access to a range of current and near-term forefront facilities at many wavelengths is critically important. This includes new instruments on HST, ALMA, JWST, and ground-based facilities such as wide-field imaging with sub-arcsecond resolution and optical spectroscopy on 8-m class telescopes. Tools to allow effective community access to data from these major missions and facilities should be built into both current and future major programs and supported over the long-term.
- Future missions such as JDEM and facilities such as TMT and ATLAS should incorporate general astrophysics programs in addition to their more specific science goals whenever possible, and plan to support these programs.
- Flexible funding structures should be supported to enable and encourage multi-facility and interdisciplinary research. Funding for theoretical work and computational modeling should be included in this, since it plays an integral role in achieving the scientific goal of understanding the formation and evolution of star clusters and their host galaxies.

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