Resolved Stellar Populations in the Milky Way

A Whitepaper Submitted to the Decadal Survey Committee

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Science Frontier Panels:
PRIMARY: Stars and Stellar Evolution (SSE)
SECONDARY: Galactic Neighborhood (GAN)

Projects/Programs Emphasized:
1. The Large Synoptic Survey Telescope (LSST); `http://lsst.org`
2. Pan-STARRS; `http://pan-starrs.ifa.hawaii.edu`
3. Thirty Meter Telescope; `http://www.tmt.org`
4. Giant Magellan Telescope; `http://www.gmto.org`

1 Abstract

The design of future wide-field imaging surveys will naturally target Milky Way star clusters with unprecedented depth and accuracy. These studies will uncover the faintest hydrogen burning main-sequence stars, substellar populations, and remnant white dwarfs, in systems that are co-spatial, co-eval, and iso-metallic. From the youngest clusters that just formed, to the oldest globulars in the Milky Way, the fundamental properties of thousands of systems will be accurately constrained with multi-band photometry (e.g., reddening, distance, metallicity, age, binary fraction, and astration mass), through the comparison of synthetic color-magnitude diagrams to the observations. These data sets serve as local calibrators for many relations in astrophysics, and therefore have widespread applications, extending to our interpretation of the properties of distant unresolved galaxies through population synthesis techniques. Follow-up spectroscopic observations of new discoveries within these star clusters will ultimately define our understanding of the interface of stellar evolution and stellar dynamics. In this whitepaper, we discuss the importance of future imaging and spectrosopic observations as it relates to the study of nearby star clusters.

2 Introduction – Open and Globular Star Clusters

Nearby star clusters in the Milky Way have served as the most important laboratories for our understanding of stellar processes. There are two distinct classes of clusters in the Milky Way, population I open clusters that are lower mass (10's to 1000's of stars) and mostly confined to the Galactic disk, and population II globular clusters (10,000s to 100,000s of stars) that are massive and make frequent excursions into the Galactic halo. These clusters are the end products of massive star formation processes such as those we see in regions like the Orion OB association today. The systems are coeval, co-spatial, and iso-metallic, and therefore represent controlled testbeds with well established properties. It is the knowledge that we've gained from studying these objects that forms our basic understanding of how stars form and evolve, and directly feeds into our ability to interpret light from unresolved galaxies in the Universe.

Despite their importance for several aspects of stellar astrophysics, many rich star clusters have been historically neglected from observational studies given their large angular sizes or distances. The advent of wide-field CCD cameras on 4-meter class telescopes has recently provided us with a wealth of new data on these systems. Both the CFHT Open Star Cluster Survey (Kalirai et al. 2001a; 2001b; 2001c, see Figure 1) and the WIYN Open Star Cluster Survey (Mathieu 2000) have systematically imaged nearby northern hemisphere clusters in multiple filters, making possible a number of new studies. Similarly, the ACS Survey of Clusters has provided homogenous imaging of a large fraction of the Milky Way's globulars (Sarajedini et al. 2007). Yet, even these projects represent pencil beam studies with respect to surveys that are on the horizon for 2010–2019.

Multi-epoch, multi-filter, deep imaging data from surveys such as **LSST**, **Pan-STARRS**, and **SkyMapper** can provide homogenous photometry of stars in all star clusters in both the northern and southern hemispheres. The photometry must be of sufficient accuracy to characterize stars stretching from the brightest giants to faint hydrogen burning dwarfs, including the bluer remnant white dwarfs of more massive evolved stars. This imaging alone is a powerful data set to answer key questions about the evolution of stars, however will benefit greatly from future multi-object spectroscopy with 30-m telescopes such as **TMT** and/or **GMT**. Below we outline some of the key scientific discoveries that can be made in 2010 – 2019 as they relate to nearby stellar populations.

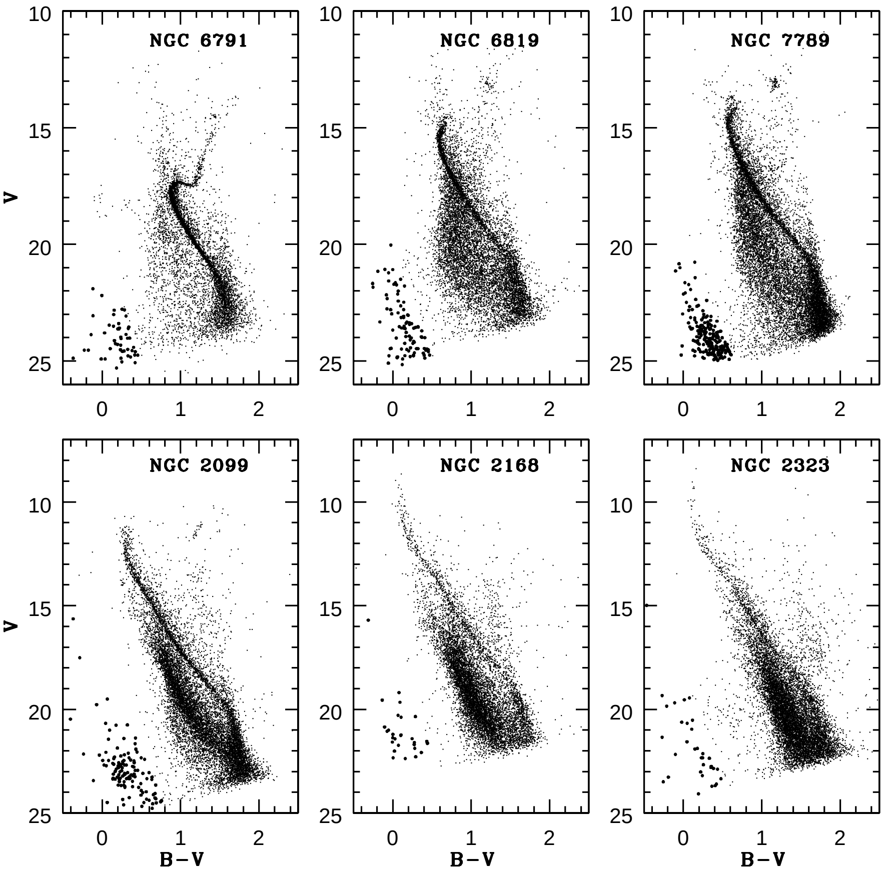

Figure 1: *Color-magnitude diagrams of six rich open star clusters observed as a part of the Canada-France-Hawaii Telescope Open Star Cluster Survey (Kalirai et al. 2001a). The clusters are arranged from oldest in the top-left corner (8 Gyr) to the youngest in the bottom-right corner (100 Myr). Each color-magnitude diagram presents a rich, long main-sequence stretching from low mass stars with* $M \lesssim 0.5\ M_\odot$ *up through the turnoff, including post main-sequence evolutionary phases. The faint-blue parts of each color-magnitude diagram illustrate a rich white dwarf cooling sequence (candidates shown with larger points).*

3 New Insights on Stellar Evolution

3.1 Background

Ejnar Hertzsprung, in 1905, found direct evidence that stars of the same temperature, and with the same parallax (and therefore at the same distance), could have very different luminosities. His initial observations led him to suggest at least two broad bins that characterize stars, bright “giants” and fainter “dwarfs”, and quickly evolved into the first Hertzsprung-Russell (H-R) Diagram (published in 1911). By adding observations of both field stars and nearby co-moving groups (e.g., the Hyades and the Pleiades), Hertzsprung and Henry Norris Russell illustrated clear evidence for groupings and sequences on the H-R Diagram and speculated on the first possible mass-luminosity relation (Russell 1913; 1914). This work led the way for stellar evolution theory.

The H-R diagram has since represented one of the most widely used plots in astrophysics and understanding stellar evolution has been one of the most important and sought-after pursuits of observational astronomy. Much of our knowledge in this field, and on the ages of stars, is based on our ability to understand and model observables in this plane. This knowledge represents fundamental input into our understanding of many important astrophysical processes. For example, stellar evolution aids in our understanding of the formation of the Milky Way (e.g., through age dating old stellar populations, Krauss & Chaboyer 2003), the history of star formation (SF) in other galaxies (e.g., by interpreting the light from these systems with population synthesis models), and chemical evolution and feedback processes in galaxies (e.g., by measuring the rate and timing of mass loss in evolved stars).

3.2 Testing Stellar Evolution Theory

With the construction of sensitive wide-field imagers on 4-m and 8-m telescopes, as well as the launch of the HST, astronomers have recently been able to probe the H-R diagram to unprecedented depths and accuracy for the nearest systems (e.g., Richer et al. 2008). These studies have made possible detailed comparisons of not only the positions of stars in the H-R diagram with the models, but also the distribution of stars along various evolutionary phases (e.g., Kalirai & Tosi 2004). Such comparisons provide for a more accurate measurement of the properties of each system (e.g., the age), and also yield important insight into the binary fraction and astration mass of the clusters. Unfortunately, these comparisons have thus far been limited to those clusters that are nearby, and for which we have such photometry, thus only sampling a small fraction of age/metallicity space.

Wide field optical surveys such as **LSST**, **Pan-STARRs**, and **SkyMapper** will provide us with homogenous photometry of star clusters in multiple bands down to well below the main-sequence turnoff, out to unprecedented distances. For example, even for the oldest stellar populations, **Pan-STARRs** will detect stars two magnitudes below the main-sequence turnoff in all northern hemisphere star clusters out to 40 kpc. Photometry below the turnoff in younger clusters at an age of 1 Gyr will extend out to $>$200 kpc. For the southern hemisphere, where no systematic survey of star clusters currently exists, **LSST** will provide an unimaginable wealth of observational data to test stellar evolution models. With a detection limit of 24 – 25th magnitude in the optical bandpasses in a single visit, and a coadded 5-σ depth in the r-band of 27.8, **LSST** will yield accurate turnoff photometry of all star clusters in its survey volume out to beyond the edge of the galaxy. For a 12 Gyr globular cluster, this photometry will extend over three magnitudes below the main-sequence turnoff.

The resulting H-R diagrams of thousands of star clusters with these surveys completely fills the metallicity/age distribution from [Fe/H] = -2, 12 Gyr globular clusters to super-solar open clusters with ages of a few tens of millions of years (including those in the LMC and SMC). The multi-band photometry will constrain the reddenings to each cluster independently, and therefore allow for detailed tests of the physics involved in the construction of common sets of models, as well as atmospheric effects. For example, slope changes along the main-sequence, such as those seen in Figure 1, as well as the morphology of the hook in the main-sequence turnoff can yield valueable insights into the treatment of convection, the importance of atomic diffusion and gravitational settling (VandenBerg, Bolte, & Stetson 1996; Chaboyer 2000), and the onset of rotation in massive stars (e.g., younger clusters). For the first time, these comparisons can be carried out in sets of clusters with different ages but similar metallicity, or vice versa, thus fixing a key input of the models. Taken further, the data may allow for new probes into the uncertainties in opacities, nuclear reaction rates, and the equation of state, and therefore lead to new understandings of both the micro and macrophysics that guide stellar evolution theory.

As we explore the inner and outer parts of the Galaxy, a full understanding of the H-R diagram at infrared wavelengths is also needed. These observations, in the near and mid-IR, will expand the abundance and age range over which these clusters formed, and provide the integrated light templates for extragalactic studies (e.g., 2MASS, **Spitzer**, **WISE**, and the **Near Infrared Sky Surveyor (NIRSS)**).

4 The Stellar Mass Function

An important goal of stellar astrophysics in our local neighborhood is to characterize the properties of low-luminosity stars on the lower main-sequence. Such studies feed into our knowledge of the color-magnitude relation and the initial mass function of stars, which themselves relate to the physics governing the internal and atmospheric structure of stars. In fact, knowledge of possible variations in the initial-mass function has wide-spread consequences for many galactic and extragalactic applications (e.g., from understanding star formation mechanisms to measuring the mass of distance galaxies). Probing these distributions in nearby star clusters, as opposed to the field, offers key advantages as the stars are all at the same distance and of the same nature (e.g., age and metallicity).

The majority of stars are belived to be formed in clustered environments like the Orion OB association. The study of individual stars in these young (¡ 10–20 Myr) associations are crucial for examination of the star formation processes which define the initial mass function and for understanding the evolution of the circumstellar disk during the planet formation epoch. Since low mass stars and brown dwarfs are both warmer and more intrinsically luminous at these ages than in evolved open clusters, determination of quantities such as the initial mass function and multiplicity fractions are possible to lower masses.

Previous surveys such as the **SDSS** and **2MASS** have yielded accurate photometry of faint M dwarfs out to distances of $\sim$2 kpc. A survey such as **LSST**, with a depth that is two and five magnitudes deeper than **Pan-STARRS** and **GAIA**, will enable the first detection of such stars to beyond 10 kpc. At this distance, the color-magnitude relation of hundreds of star clusters will be established and permit the first systematic investigation of variations in the relation with age and metallicity. The present day mass functions of the youngest clusters will by dynamically unevolved, and therefore provide for new tests of the variation in the initial mass function as a function of environment. Even for the older clusters, the present day mass function can be related back to the initial mass function through dynamical simulations (e.g., Hurley et al. 2008).

5 The Hydrogen Burning Limit and Beyond

Pushing studies of the color-magnitude relation in large samples of stellar populations to the hydrogen burning limit and beyond will benefit greatly from new space based observations. The depths reached by a survey such as **LSST** will completely characterize the lowest mass main-sequence stars in the nearest stellar populations. At an age of 1 Gyr, a M = 0.08 $M_{\odot}$ star has M_V = 19 (Baraffe et al. 1998) and will therefore be seen by **LSST** to 500 pc. However, this star has a $V - H$ color of 8, and therefore is much brighter in the near-infrared. Future all sky surveys similar to **2MASS**, such as the **Near Infrared Sky Surveyor (NIRSS)**, propose a depth of 24th magnitude in the J, H, and K filters, and therefore will easily identify the hydrogen burning limit in all star clusters out to 2.5 kpc. These data will permit the first detailed tests of the threshold mass signifying hydrogen vs deuterium burning in stars (e.g., Chabrier et al. 2005), and therefore feeds directly into our knowledge of star formation.

Such studies will also extend to sub-stellar objects, probing below the hydrogen-burning limit. At the brighter end, **LSST** will provide volume complete samples of TO brown dwarfs to $\sim$250 pc, more than six times further than even possible with **Pan-STARRS** photometry limits. **LSST** will therefore produce a sample of these stars that is more than an order of magnitude larger than comparable efforts with **Pan-STARRS** and **GAIA**, enabling statistically robust measurements of the luminosity function and color-magnitude relation in the nearest clusters.

6 A Complete Mass Function of Stars: Linking White Dwarfs to Main-Sequence Stars

The bulk of the mass in old stellar populations is now tied up in the faint remnant stars of more massively evolved progenitors. In star clusters, these white dwarfs can be uniquely mapped to their progenitors to probe the properties of the now evolved stars. For example, the imaging surveys discussed above will uncover rich white dwarf cooling sequences in thousands of star clusters. The tip of the sequence, formed from the brightest white dwarfs, is located at $M_V \sim 11$ and will be seen in a survey such as **LSST** in clusters out to 20 kpc. For a 1 Gyr (10 Gyr) cluster, the faintest white dwarfs have cooled to M_V = 13 (17), and will be detected in clusters out to 8 kpc (1 kpc). These white dwarf cooling sequences not only provide direct age measurements (e.g., Hansen et al. 2007) for the clusters (and therefore fix the primary parameter in the theoretical isochrone fitting discussed earlier, allowing secondary effects to be measured), but also can be followed up with current (**Keck**, **Gemini**, and **Subaru** and future (e.g., **TMT** and/or **GMT**) multi-object spectroscopic instruments to yield the mass distribution along the cooling sequence. These mass measurements represent the critical input to yield an initial-final mass relation (Kalirai et al. 2008), and therefore provide the progenitor mass function above the present day turnoff. The relations, as a function of metallicity, will also yield valuable insight into mass loss mechanisms in post main-sequence evolution and test for mass loss-metallicity correlations. The detection of these white dwarfs can therefore constrain the AGB and PN phases of stellar evolution, which are difficult to model (Habing 1996; Weidemann 2000). Further information on white dwarfs and their connection to stellar evolution is provided in the whitepaper by J. Kalirai on “White Dwarfs as Astrophysical Probes”.

7 Stellar Dynamics

To fully understand the stellar content of these clusters, a full characterization of the binary population is needed. The distribution of secondary masses is crucial to completely define the cluster initial mass function. Binaries are also a key component to understand the interface of dynamical and stellar evolution in clusters, which results in star systems which could not be created in isolation (e.g., blue stragglers, sub-sub giants). Addressing these questions will require deep optical and infrared photometry, with follow-up ground based spectroscopy.

Of particular interest is the blue straggler population of star clusters. These objects are the longest known cases of an increasing array of stars unexplained by standard single-star evolutionary theory, and indeed more populations are likely hidden within the main sequences. Some facets of these stars, such as the high masses in S1082 in M67, cannot be explained without inclusion of stellar dynamics. These cases point to the importance of collisions and mergers. Others can be explained as products of classical mass transfer processes. Even here, N-body simulations show that binary encounters often form or tighten, and sometimes widen, the close binaries that ultimately go through mass transfer (Hurley et al. 2005). This mix of mass transfer and stellar dynamics is also seen in the bimodal radial distributions of blue stragglers (Ferraro & Lanzoni 2008). All of these lines of evidence indicate that among the anomalous stars are the tracers of the interface of stellar dynamics and stellar evolution.

Characterizing the properties of binaries and blue stragglers will require precise (0.15 – 0.3 mas/yr) proper-motion measurements to a faint limit of V = 24 – 26, and precise (0.4 km/s) multi-epoch radial-velocity measurements to the luminosity of M dwarfs, both complete to the cluster tidal radii. Such data can provide highly reliable three-dimensional kinematic membership determinations for the entire evolved cluster population; superb two-dimensional kinematic membership determinations for cluster members to masses as low as 0.5 $M_{\odot}$; and a census of the hard binary population among the solar-type stars, with binary orbit solutions for periods up to $>$100 days. These results will need to be supplemented with optical, near- and mid-infrared photometry to further define the binary populations to masses as low as 0.5 $M_{\odot}$ and the longer-period (soft) binary populations of distant open clusters.

8 Global Properties of the Cluster Population

The temporal coverage of surveys such as **LSST** and **Pan-STARRS** will provide a means for accomplishing the above goals on a proper-motion cleaned data set. To date, only a few star clusters have such data down to the limits that these surveys will explore (these are large **HST** data sets of specific, nearby systems). Tying the relative motions to an extragalactic reference frame provides a means to measure the space velocities of these systems (e.g., Kalirai et al. 2007) and therefore constrain their orbits in the Galaxy. As open and globular clusters are largely confined to two different components of the Milky Way, these observations will lead to the use of each of the clusters as a dynamical tracer to map the potential of the Milky Way and help understand formation processes of the disk and halo (e.g., combining the 3-d distance, metallicity, age, and star cluster orbit).

Baraffe, I., et al. 1998, A&A, 337, 403

Chaboyer, B. 2000, The Galactic Halo, 451

Chabrier, G., et al. 2005, astro-ph/0509798

Ferraro, F R., & Lanzoni, B. 2008, IAUS, 246, 281

Habing, H. J. 1996, ARAA, 7, 97

Hansen, B. M. S., et al. 2007, ApJ, 671, 380

Hertzsprung, E. 1905, Zeitschrift fur Wissenschaftliche Photographie, 3, 442

Hertzsprung, E. 1911, Publ. Astrophys. Observ. Potsdam, 22, 1

Hurley, J. R., et al. 2008, AJ, 135, 2129

Kalirai, J. S., et al. 2001a, ApJ, 122, 257

Kalirai, J. S., et al. 2001b, ApJ, 122, 266

Kalirai, J. S., et al. 2001c, ApJ, 122, 3239

Kalirai, J. S., & Tosi, M. 2004, MNRAS, 351, 649

Kalirai, J. S., et al. 2007, ApJL, 657, 93

Kalirai, J. S., et al. 2008, ApJ, 676, 594

Krauss, L. M., & Chaboyer, B. 2003, Science, 299, 5603

Mathieu, R. D. 2000, ASP Conf. Ser. 198, 517

Richer, H. B. et al. 2008, AJ, 135, 2141

Russell, H. N. 1913, The Observatory, 36, 324

Russell, H. N. 1913, The Observatory, 37, 165

Sarajedini, A., et al. 2007, AJ, 133, 1658

Vandenberg, D. A., Stetson, P. B., Bolte, M. 1996, ARA&A, 34, 461

Weidemann, V. 2000, A&A, 363, 647