PROPOSAL ABSTRACT:

Chilean P.I.:	Doug Geisler
Chinese P.I.:	Baitian Tang
Proposal Title:	Investigating Formation and Chemical Evolution of the Galaxy using Star Clusters
Host Institute in Chile:	Department of Astronomy, University of Concepcion
Host Institute in China:	School of Physics and Astronomy, Sun Yat-sen University

The primary goal of this proposal is to study the formation and chemical evolution of different components of the Galaxy using multiwavelength observations of star clusters (SCs). SCs are of paramount importance in the investigation of a wide variety of fundamental astrophysical phenomena. One of the major goals of modern astronomy is an understanding of galaxy formation. SCs, especially the ancient globular clusters (GCs), are perfect tools for this study, as they were both witnesses to the epoch of major Galactic formation and are still present today. In addition, we can derive their ages, velocities and detailed chemical abundances to help unravel the process of formation and evolution using both temporal, chemical and kinematical evidence. SCs, including GCs and open clusters (OCs), are present in all major components of the Galaxy, including the halo, bulge, thin and thick disks, and thus can be used to study the histories of all these Galactic structures. We will place special emphasis on Galactic bulge GCs, given their importance, the primordality of the bulge and our growing expertise in this field. A secondary goal of this project is to further our observational database concerning the fascinating phenomenon of multiple populations in SCs. The longstanding notion that Galactic GCs are quintessential Simple Stellar Populations is now overthrown by the discovery of multiple populations (MPs) in an increasing number of GCs (but so far apparently not in younger and less massive OCs). They appear to be almost ubiquitous in old, massive GCs, thus forcing a paradigm shift in our understanding of their formation. Before we can formulate a proper theoretical framework for their origin, further detailed, comprehensive observational data, both spectroscopic and photometric, are badly needed to help constrain any models. Our group at Universidad de Concepcion has been intensely involved in a longterm project aimed at obtaining ages and abundances, as well as velocities, for a variety of SCs in different Galactic components, as well as investigating MPs in a wide variety of SCs. We are currently involved in several ongoing large Galactic photometric and spectroscopic surveys that should prove to be even more fruitful and powerful in the study of SCs and their application to the above-mentioned areas of astrophysics. In particular, we are heavily involved in the APOGEE and Gaia-ESO surveys. Using these ongoing Galactic spectroscopic surveys with high resolution multi-object spectrographs, we will explore the detailed chemical patterns of giant members in GCs and OCs. At the same time, LAMOST, which is recently proven to be able to derive 14 chemical abundances, is used to study many of these same astrophysical goals. Our aim is to join forces and study in particular the chemical abundances of stellar components in SCs using these large surveys that we are part of. Adding a joint postdoc will help us to forge a collaboration between our two institutions, building on our already existing strong personal collaboration, and allow us to maximize the scientific output. Our privileged access to the world-class observational facilities in Chile will allow us to obtain follow-up observations of particularly important SCs. The proposed work is observationally oriented, but theoretical models will also be used to guide the astrophysical interpretations.

SCIENTIFIC JUSTIFICATION

One of the major goals of modern astronomy is an understanding of galaxy formation. An ideal tool for this study would be a witness which was both present at the long-since-vanished first epoch when most galaxies formed, and yet still survives today to tell us its story. In addition, we would like many such witnesses, to corroborate their stories, we would like them to be readily visible and to yield such critical information as their age and chemical composition in a well-understood, easily measured and precise way. Enter the GCs. They are among our most powerful cosmological probes for investigating this key topic. They have proven to be especially vital in piecing together the assembly history of our own Galactic halo.

The Galactic bulge (GB) is one of the most massive Milky Way components and directly linked to the formation mechanisms of various Galactic structures, such as the bar(s). The GB GCs are particularly important: as Shapley famously realized, the GB contains a disproportionately large number of them, which we now recognize form an independent GC system from that of the halo. Because galaxies most likely form from the inside-out, the metal-poor stellar population in the inner few kpc of the GB is the best place to search for the oldest stars in the Galaxy. **The bulge GC system very likely contains the oldest object in the Galaxy for which we can obtain a very accurate age**, allowing us (once we find it) to strongly constrain the answer to such profound questions as how long after the Big Bang did the Galaxy begin to form and how? Unfortunately, until recently we have not been able to unleash the full power of the GB GCs to help unravel its history. The GB, despite its proximity and central role as a primary primordial component of the Galaxy, has resisted detailed investigation due to its high extinction that strongly limits optical observations. However, these effects are minimized by observing in the near IR, allowing us to fully exploit the GB GC's extraordinary archeological attributes.

A key initial step was the recently completed first phase of the Vista Variables in the Via Lactea (VVV) ESO public near-IR imaging survey of the GB and an adjacent strip of the inner disk, of which we form an important part of the GB team. We are also involved in VVVX, the new 3-year extension. Our group has taken full advantage of this exquisite database to study the GB GCs. We have discovered new GC candidates, found dual horizontal branches in two massive metal-rich GB GCs, investigated structural parameters for a number of them and provided the deepest VVV-based CMDs to date. In addition, we have obtained even deeper near-IR followup imaging with GeMS+GSAOI on Gemini South for a sample of GCs. A very precise age can be determined from such data. However, to derive the best GC ages, and hence pin down the earliest formation epoch of the Galaxy with the smallest error possible, requires both deep photometry as well as high-resolution spectroscopy to derive the detailed abundances required for isochrone-fitting. What is lacking are good [Fe/H], [α/Fe] and [CNO/Fe] values. All CMD-based age diagnostics are sensitive to these key elements. Given exquisite near-IR photometry now in our possession, **the single remaining yet very significant uncertainty on GC ages is their chemical abundances.**

With the arrival of the APOGEE-2S IR multifiber spectrograph on the Las Campanas Observatory du Pont telescope as part of the Sloan Digital Sky Survey IV, the missing link of obtaining abundances in GB GCs is now feasible. Incredibly, most of these invaluable objects only have very poor estimates of the overall metallicity or mean radial velocity, based on a variety of techniques, making for a very heterogeneous sample rife with poorly determined values as well as their errors. We recently proposed **CAPOS, the bulge Cluster APOgee Survey** to the CNTAC. **This is a long term project to obtain detailed abundances as well as kinematics for a complete sample of true GB GCs. The CAPOS project has been granted an initial two nights in the CNTAC 2018-A period,** which we hope will eventually be awarded the full long-term status. APOGEE-2S will provide much better and completely self-consistent spectroscopic metallicities and velocities than currently available for hopefully all of the sample, as well as provide detailed abundances for a large number of elements with a wide variety of nucleosynthetic origins for many member giants per cluster. Recognizing their importance, the SDSS-IV survey will study some of the GB GCs with APOGEE-2S. However, they will only observe 6 of the bonafide GB GCs lying within 10° of the Galactic center, while **CAPOS will observe the remaining 29 bonafide GB GCs, or 81% of the total, making for a combined 100% complete sample** (if granted full long-term status). Note that we are part of the SDSS-IV survey and thus have access to the survey data, while D. Geisler is the PI of the CAPOS project, and B. Tang is a Co-I of the project.

We will also search for multiple populations (MP) within GB GCs. The recognition of MP in GCs has revolutionized our understanding of their formation and evolution, but so far this study has been limited almost exclusively to non-GB GCs. APOGEE includes lines of the critical light elements C, N, Na, O, Mg and Al which are essential to trace MPs. Indeed, several of the GB GCs have already been observed by APOGEE-1 as part of SDSS-III. In a recent paper led by Baitian Tang, we have analyzed this data to search for MPs in NGC 6553, the GB GC with the largest sample of members observed with APOGEE-1. We clearly detect MPs, suggesting that whatever the mechanism responsible for this phenomenon also operated in GB GCs as well as their halo counterparts, even at this very high (nearly solar) metallicity. Our group clearly has already established itself as a world leader in this field and thus has the experience and expertise to conduct this research when the new data become available. What is missing, and crucially important, is the manpower to attack the reduction and analysis of this database, hence this request for a postdoc.

We will pursue similar scientific goals in GCs and OCs in other Galactic components in addition to the GB using ongoing very widefield Galactic spectroscopic surveys with medium to high resolution multi-object spectrographs, including APOGEE, the Gaia-ESO survey and LAMOST, in which we are all involved. In recent years, such large-scale Galactic spectroscopic surveys have greatly improved our knowledge about the chemical and kinematic properties of the Milky Way by providing high quality spectra for more than $\sim 10^5$ stars. However, there is much further data-mining of the current database to be done to extract the maximum information, as well as to be poised to be the first to explore new data as it emerges, given our proprietary access. We will examine the detailed chemical patterns of a large number of elements in giant members of SCs in the halo, thin and thick disks. The LAMOST Experiment for Galactic Understanding and Exploration (LEGUE) survey of Milky Way stellar structure has proven to be very successful, with the discovery of a large number of interesting stars relevant to our investigation, e.g. carbon-enhanced metal-poor (CEMP) stars. Recently, machine learning has been shown to be able to derive abundances for 14 elements from the LAMOST spectra. This further extends the possible scientific discoveries from the LAMOST data. The fact that the training set of this method is APOGEE spectra with SDSS-IV pipeline parameters proves the great potential for synergy between these two surveys.

CONNECTIONS WITH INSTITUTES IN CHILE AND CHINA

Doug Geisler, the Chilean P.I., is a full professor in the Department of Astronomy, University of Concepcion, who specializes in photometry and spectroscopy of individual stars in star clusters. Other astronomers in the group are Sandro Villanova and Jose Fernandez-Trincado. Sandro is an associate professor, whose expertise is mainly on obtaining stellar abundances from high-resolution spectra. Jose is the targeting field selection coordinator of the APOGEE-2 south survey. He is also experienced in Galactic dynamics and chemical abundances of individual stars.

Baitian Tang, the Chinese P.I., is an associate professor in the School of Physics and Astronomy, Sun Yat-sen University. Baitian joined Sun Yat-sen University recently, and before that, he was a postdoc working in Doug's group, where they forged a strong research collaboration in this field. Doug and Baitian and the other group members in Concepcion have published a number of papers together in chemical abundances. He is specialized in deriving the chemical abundances from the APOGEE spectra.

IMPLEMENTATION

This is expected to be a three year project. The postdoc candidate is expected to spend the first 2 years in Chile, and the last year in China.

First year:

- The postdoc joins the APOGEE, Gaia-ESO and LAMOST surveys, and becomes familiar with the data structure and analysis techniques of these surveys.
- Learning how to derive the chemical abundances from the APOGEE spectra.
- Writing observation proposals about GC MPs using Chilean time.
- Observation of GCs via the CAPOS project in Chile.
- Reducing GC star spectra from the CAPOS observation or from APOGEE-2S.
- Writing paper about the initial results and presenting them at international conference

Second year:

- Observation of GCs via the CAPOS project in Chile.
- Reducing GC star spectra from the CAPOS observation or from APOGEE-2S.
- Writing paper and observation proposals about MP research.
- Writing paper and presenting results from the GCs observed by the CAPOS projects or from APOGEE.

Third year:

- Observation of GCs via the CAPOS project in Chile.
- Reducing GC star spectra from the CAPOS observation or from APOGEE-2S.
- Writing paper and observation proposals about MP research.
- Writing paper and presenting results from the GCs observed by the CAPOS projects or from APOGEE.