JMU RD9R (2012/vs3) date received by FRC

LIVERPOOL JOHN MOORES UNIVERSITY

Application to Register for a JMU Research Degree
(This application must be typed)

Submitted by the School of Engineering (Astrophysics Research Institute)

for the degree of *(delete as appropriate)*:

(iii) Master of Philosophy (MPhil) with transfer possibility to Doctor of Philosophy (PhD)

Enrolment No. 778459

Mode of study: Full-time

1. The Applicant

Name: Silvia Martocchia Female Date of Birth: 15/11/1991

Private Address: 39 Ampleforth House, Dial Street, Warrington, WA1 2NX

Present post and place of work:
PhD Student, Astrophysics Research Institute, Liverpool John Moores University

Particulars of any scholarship or other award held in conjunction with the proposed research programme:
LJMU PhD studentship scheme

Qualifications gained (include places[s] of higher education, courses completed, main subjects, classification of award, date and name of awarding body - see Regulations G3.3, 3.4 and 3.5):

Astronomy and Astrophysics, MSci (First Class Honours)

Name of awarding body : “Università degli studi di Roma, La Sapienza”

Date of Award: 22/10/2015

Physics and Astrophysics, BSc (First Class Honours)

Name of awarding body : “Università degli studi di Roma, La Sapienza”

Date of Award: 02/10/2013

Training and experience (include details of activities [with dates] relevant to this application, and of any research or other relevant papers, books, etc, which have been published - see Regulations G3.4 and 3.5):

N/A

2. Academic Referees (see Regulation G3.4)

* delete as appropriate

N/A

3. Name of Collaborating Establishment (see Regulation G1.5)

N/A

4. The Programme of Research

4.1 Title of the proposed investigation:

Searching For Multiple Populations in Massive Young and Intermediate Age Clusters

4.2 Aim of the investigation:

The aim of this project is to pin-point the physical property which regulates whether a cluster can host multiple populations. Specifically, several key goals are:

- Analyse colour-magnitude diagrams of massive star clusters, spanning a wide range of ages;
- Compare cluster observations with stellar evolution models to determine the presence of multiple populations;
- Determine whether age can play a major role in the multiple population phenomenon.

4.3 Proposed plan of work, including its relationship to previous work, with recent key references:
(Please continue on separate sheet(s) if necessary)

BACKGROUND

Once thought to be formed by simple stellar populations, where each star has approximately the same abundance and age, globular clusters (GCs) have been observed to host multiple populations (MPs) of stars. This evidence has manifested through light elements abundance spreads (C, N, O, Na, Al and Mg), which are not observed in field stars of the same metallicity. These spreads also show intriguing relations in some elements, i.e. the Na-O anti-correlation (Carretta et al. 2009) and the C-N anti-correlation (Cannon et al. 1998). Furthermore, evidence for chemical variations may be assessed through photometry, by looking at splittings and/or spreads in the clusters colour-magnitude diagrams, from the Main Sequence (MS), up to the Red Giant Branch (RGB) and Horizontal Branch (HB), by using certain colour combinations (e.g., Piotto et al. 2015).

The origin of MPs is still under debate (e.g., D'Antona et al. 2014, Bastian et al. 2015), and multiple models have been put forward. In the most popular models, secondary populations of stars are formed from the ejecta of higher-mass evolved stars from the first generation along with "pristine" material (i.e., primordial material, with the same chemical abundances as the first generations). Three main agents for the enrichment have been suggested: (i) AGB (Asymptotic Giant Branch) stars (e.g., D'Ercole et al. 2008), (ii) Fast-rotating massive stars (FRMS, Decressin et al. 2007) and (iii) Interacting massive binary stars (de Mink et al. 2009). The main idea behind these models is that a first generation of stars forms and removes any gas not used in star-formation. After about 30 Myr, AGB stars begin to evolve which shed He-enriched material into the cluster. This material collects in the centre of the cluster, and the cluster re-accretes pristine material from its surroundings. The pristine and accreted materials partially mix, and a second burst (and potentially more) of star-formation happens within the cluster. A similar model is envisioned for the “spin-star” scenario, but instead of needing 30 Myr to begin collecting material for further epochs of star-formation, the enriching stars are rapidly rotating massive stars, which begin shedding material from a very early age. All three of the above mentioned models suffer from a severe “mass-budget” problem. In order to reproduce observations (that 1st/2nd generation stars are in roughly equal ratio in GCs today), the models require that the first generation stars was significantly more massive at birth. This extra-mass is lost to the field of the host galaxy. However, Bastian & Lardo (2015) recently showed how the fraction of enriched stars in GCs remains constant with distance and mass, in conflict with expected correlations resulting from a proposed mass-loss due to tidal stripping or gas expulsion. A new alternative scenario for the origin of MPs was recently proposed, e.g. Bastian et al. (2013b), which includes a single burst of star-formation. This is called the “Early Disc Accretion” (EDA) scenario, where spin-stars and interacting binaries material shed enriched material into the cluster, and low-mass pre-MS stars with protoplanetary discs are able to sweep up the enriched material and eventually accreted it onto the host stars. Unlike the previous models, this does not suffer from the a mass budget problem, but has other potential caveats, such as difficulties in reproducing the chemical trends with lithium.

The presence of multiple populations in globular clusters appears to be ubiquitous in the most nearby galaxies. Milky Way GCs have been largely studied (Gratton et al. 2012) and all old (i.e., >10 Gyr) clusters surveyed so far have been found to host MPs, as well as in the Fornax dwarf galaxy (Larsen et al. 2014), in the Sagittarius dwarf galaxy (Carretta et al. 2014) , in the Large Magellanic Cloud (LMC, Mucciarelli et al. 2009) and in the Small Magellanic Cloud (SMC, Niederhofer et al. 2016, Hollyhead et al. 2017). Intriguingly, no young or intermediate age (1-2 Gyr) massive clusters have been found with abundance variations within them (Mucciarelli et al. 2014). The favoured explanation for this was that GCs were simply more massive at birth, leading to the suggestion that cluster mass is the crucial parameter controlling whether a cluster hosts MPs. However, as stated above, this concept has lately been questioned, pointing towards new searches for the key parameter. An alternative view is that GC formation was fundamentally different than the formation of older massive clusters. The proposed project aims at addressing the question whether the presence of MPs in globular clusters could be identified based on the cluster's age. This is an observational-based project entailing an exploratory surveyof the stellar populations in young globular clusters.

METHOD

Prof. Bastian and his group have recently obtained observing time with Hubble Space Telescope (HST/WFC3) of 12 massive (> 10^5 Msun) clusters within the LMC/SMC, spanning a wide range of ages (100 Myr – 10 Gyr). The goal of this project is to determine if there is an age or mass limit to the presence of multiple populations in clusters. The study of MPs has undergone a revolution in the past few years due to the discovery that they can be found in high-precision colour-magnitude diagrams (CMDs) of GCs based on the strength of spectroscopic features, sensitive to the elements that vary between populations, within the bandpasses of certain WFC3 filters (e.g., F275W, F336W, F343N). Using the resolved CMDs in these specific filters, the presence of multiple populations can be seen for hundreds to thousands of stars at a time for various evolutionary states. Specifically, the presence of a strong NH molecular band within the F343N filter has been used to uncover and study MPs within galactic and extragalactic GCs (Larsen et al. 2014; 2015). The strength of the NH band is an excellent indicator of the nitrogen abundance of stars and is largely independent of age. For the present project we will be making use of HST images in the F336W, F343N, and F438W (along with complimentary optical imaging available on the archive).

In addition to the HST data, we will also use specifically tailored stellar isochrone models, within which the chemical signatures of MPs have been included (see Niederhofer et al. 2016 for a description of the models). These isochrones allow us to determine the best way to search for MPs within our dataset, as well as place constraints on the type of variations present (i.e. what N-variations are needed to explain the data, or what N-variations can be ruled out if MPs are not detected).

So far, Niederhofer et al. (2016) detected MPs in the old (t=10 Gyr) SMC cluster NGC 121. This served largely to validate the techniques used to detect MPs. In a second study, Niederhofer et al. (2017, in press) discovered MPs within other 3 intermediate age (6-8 Gyr) SMC clusters (Lindsay 1, NGC 339, and NGC 416). These results were confirmed by Hollyhead et al. (2016) who spectroscopically detected MPs in the SMC cluster Linsday 1, still massive (10^5 Msun) and relatively young (8 Gyr old). Also, Hollyhead et al. in prep. detected MPs in another ~6 Gyr old SMC cluster, i.e. Kron 3. These studies have demonstrated that MPs are not limited to only the ancient GCs but are present in clusters with ages at least as young as 6 Gyr. This corresponds to a formation redshift of z=0.65, which is well past the peak of GC formation in the Universe (z=2-3; Brodie & Strader 2006).

The next step of the project will be for the PhD student to study the remain clusters of the sample, focussing on the younger (1-2 Gyr) old clusters. This sample consists of five clusters (NGC 1806, 1846, 419 and 1978, 1783). These clusters have masses in excess of the 6-8 Gyr sample that have already been found to host MPs. So if MPs are not found within these clusters, it will be clear proof that mass is not the controlling parameter with regards to the presence of MPs.

The student will follow these steps in order to search for MPs within these clusters. The reduced photometric catalogues have already been provided by a collaborator working at the Space Telescope Science Institute (Dr. Vera Platais). First, the student will select likely cluster member stars by statistically subtracting the background/foreground field star population (Niederhofer et al. 2016). Second, the student will correct for differential extinction across the cluster using the method by Milone et al. (2012). The next step is to estimate the age, extinction and distance modulus for each cluster based on comparison between the observed CMD and the MIST isochrones (Choi et al. 2016). Once the best set of parameters is known for each cluster, specifically tailored isochrones will be made including the anomolous chemistry of MPs. These models will be provided by Dr. Chris Usher who is a postdoctoral researcher within the group. Finally, the student will quantitatively compare the observed CMDs to the model predictions, with and without MPs, in order to determine whether MPs are present. The focus for this step is on the red giant branch (RGB) which is the part of the CMD where MPs are most readily discernible.

The first cluster that will be studied is NGC 419, due to its low field star contamination rate, low extinction, and location in the SMC where the 6-8 Gyr clusters have been found to host MPs. A first paper will then be written on the results of the cluster analysis. This is expected to be submitted before the end of 2016. Once this is submitted, the student will focus on the other 4 intermediate age (1-2 Gyr) clusters, and will write up these results in a follow up paper.

MOTIVATION, IMPACT AND SIGNIFICANCE

The origin of multiple populations, seen in nearly all massive and old GCs is still unknown, with all suggested scenarios having severe shortcomings. GC mass has been traditionally assumed to be the dominant factor in the onset of MPs, but recent photometric and spectroscopic studies suggest that age plays an important role. It is currently unknown whether clusters in the age <1-2 Gyr have MPs, potentially the youngest cluster at present with them being aged 6.5 Gyr (Kron 3, Hollyhead et al. In prep.). The targets proposed in this survey will probe this age range and allow to more fully constrain the age and mechanism for the onset of MPs. They will allow to identify the key parameter that controls whether a cluster hosts MPs, i.e. is it simply a mass/density limit, or, if no young/intermediate age clusters are found to host MPs, is it a feature of cluster formation in the early Universe?
The detailed characterisation of MPs is a crucial ingredient for any theoretical scenarios aimed at explaining the origin of GC chemical inhomogeneities.

Furthermore, the presence and nature of MPs has consequences for GC formation theories, which currently cannot account for all the observed abundance variations (Bastian et al. 2015) without significant issues (e.g. mass budget problem; Larsen et al. 2012, Bastian & Lardo 2015, Kruijssen 2015). Without a working theory for how MPs are created, GC formation theory is still incomplete, which also has consequences for galactic formation theory as populations of stars with similar abundance patterns have also been identified in the bulge of the Milky Way (Schiavon et al. 2016).

The ongoing HST survey with photometry available for clusters spanning a wide age range is and will be complimented by results in spectroscopy (VLT/FORS2 spectra). So far it has been found that all clusters older than ~ 6 Gyr show evidence for MPs, whereas younger clusters show mixed results. It is necessary to further probe ages below 6.5 Gyr to try to constrain these different results and provide a clearer picture of cluster properties at this age. New age ranges will be investigated, providing further constraint to the age at which MPs are present or observable.

In order to constrain GC formation theories, young massive clusters (YMCs) have been used as potential pre-cursors to GC systems (e.g. Cabrera-Ziri et al. 2015). However a lack of MPs within YMCs has introduced some uncertainty whether this can be the case and it has been suggested that GCs formed in different conditions in the early universe. The discovery of MPs in younger clusters indicates that the formation processes that shape GCs into what we see today should not be applicable to only old GC systems. By looking for evidence of MPs in even younger clusters and constraining their onset, we can confirm whether YMCs can be considered very young potential future GCs.

The potential of this PhD project is to dig deeper into the unknown origins of the phenomenon of multiple populations. What causes it and what does it depend on? Addressing these questions is challenging, however this work will provide powerful observational insights ready to be exploited to develop new models and theories.
Work carried out by the student should lead to at least two or three first author publications, which will be carried out using data which in the most part is exclusive and not yet publically available, so will represent fundamental science at the origin of MPs scenario.

TIMELINE
October 2016 – December 2016: Literature review. Begin working on NGC 419 to determine whether multiple populations are present. Write up the results for publication.

January 2017 – April 2017: Analyse the CMDs of NGC 1806, 1846, 1978 and 1783 to search for multiple populations.

May 2017 – September 2017: Write up the results for the studied clusters.

October 2017 – November 2017: Write transfer report to PhD and submit. Deliver transfer viva.

December 2017– April 2018: Learn to reduce HST data and carry out PSF photometry along with completeness calculations.

May 2018 – December 2018: Learn to reduce/analyse high/medium resolution spectroscopy from the VLT to study 1) stellar rotation and 2) chemical abundances. Apply for new data as well as exploit existing VLT programmes being carried out by the group.

January 2019 – March 2019: Write up the results.

April 2019– September 2019: Expand parameter space (extragalactic, unresolved massive clusters) where MPs have been searched for. Write up results and complete thesis.

<u>REFERENCES</u>

Bastian N., Cabrera-Ziri I., Salaris M., 2015, MNRAS, 449, 3333
Bastian N., Lamers H. J. G. L. M., de Mink S. E., Longmore, S. N., Goodwin S. P., Gieles M., 2013, MNRAS, 436, 2398
Bastian N., Lardo C., 2015, MNRAS, 453, 357
Brodie J. P., Strader J., 2006, ARA&A, 44, 193
Cabrera-Ziri I. et al., 2015, MNRAS, 448, 2224
Cannon R. D., Croke B. F. W., Bell R. A., Hesser J. E., Stathakis R. A., 1998, MNRAS, 298, 601
Carretta E., Bragaglia A., Gratton R. G., D'Orazi V., Lucatello S., Sollima A., 2014, A&A, 561, A87
Carretta E. et al., 2009, A&A, 505, 117
Choi J., Dotter A., Conroy C., Cantiello M., Paxton B., Johnson B. D., 2016, ApJ, 823, 102
D'Antona F., Ventura P., Decressin T., Vesperini E., D'Ercole A., 2014, MNRAS, 443, 3302
de Mink S. E., Pols O. R., Langer N., Izzard R. G., 2009, A&A, 507, L1
Decressin T., Meynet G., Charbonnel C., Prantzos N., Ekström S., 2007, A&A, 464, 1029
D'Ercole A., Vesperini E., D'Antona F., McMillan S. L. W., Recchi S., 2008, MNRAS, 391, 825
Gratton R., Carretta E., Bragaglia A., 2012, A&ARv, 20, 50
Hollyhead K. et al., 2017, MNRAS, 465, L39
Kruijssen J. M. D., 2015, MNRAS, 454, 1658
Larsen S. S., Baumgardt H., Bastian N., Brodie J. P., Grundahl F., Strader J., 2015, ApJ, 804, 71
Larsen S. S., Brodie J. P., Grundahl F., Strader J., 2014, ApJ, 797, 15
Larsen S. S., Strader J., Brodie J. P., 2012, A&A, 544, L14
Milone A. et al., 2012, A&A, 540, A16
Mucciarelli A., Dalessandro E., Ferraro F. R., Origlia L., Lanzoni B., 2014, ApJ, 793, L6
Mucciarelli A., Origlia L., Ferraro F. R., Pancino E., 2009,ApJ, 695, L134
Niederhofer F. et al., 2016, MNRAS
Piotto G. et al., 2015, AJ, 149, 91
Schiavon R. P. et al., 2016, ArXiv e-prints

4.4 Details of facilities available for the investigation (including funding and location):

LJMU library facilities
Access to all subscribed academic journals by LJMU in the appropriate fields
ARI computer cluster
Telescope Observations - HST

4.5 Relationship between work to be undertaken in the collaborating establishment and that to be undertaken at the sponsoring establishment or elsewhere (see Regulation G1.5):

N/A

* delete as appropriate

4.6 Is ethical approval required?
Registration will not be approved by the Research Degrees Committee until such approval has been granted where necessary (see Regulation G4.9):

N/A

5. The Programme of Related Studies (Complete *either* 5.2 *or* 5.3)

5.1 Have you attended the Research Student Induction organised by the Graduate School? (see Regulation G4.10):

Yes – 24/11/2015

5.2 Details of programme of related studies to be undertaken (see Regulations G4.1 and 4.7):

Seminars at the ARI (weekly)
Meetings with Star Formation and Stellar Population Group at ARI (weekly)
Research training sessions with academic staff at ARI (monthly)
Regular meetings with primary supervisor (at least bi-weekly)
Meetings with Multiple Populations Group at ARI (bi-weekly/monthly)
Attendance at national/international conferences
3is Training

5.3 Where an integrated programme of study is proposed, details of the course of postgraduate study on which the candidate's performance is to be formally assessed are required (see Regulation G4.4):

N/A

6. Supervision of Programme of Work (see Regulations G6.1 to 6.6)

In the case of a PhD registration please indicate which supervisors have successfully supervised at PhD level.

Note: attendance at supervisor training is requested of all new supervisors

6.1 Director of Studies *(include name, qualifications, post held and place of work):*

Professor Nathan Bastian, PhD, Head of Research, Astrophysics Research Institute, LJMU

Experience of supervision of *registered* research degree candidates:

Currently supervising as Director of Studies 3 Full-Time 0 Part-Time UK university candidates
Currently registered as 2nd / 3rd supervisor for 2 Full-Time 0 Part-Time UK university candidates
Previously supervised 0 UK university/CNAA candidates (successfully completed supervision)

6.2 Second Supervisor *(include name, qualifications, post held and place of work):*

Professor Maurizio Salaris, PhD, Professor of Stellar Astrophysics, Astrophysics Research Institute, LJMU

Currently supervising as Director of Studies 2 Full-Time 1 Part-Time UK university candidates
Currently registered as 2nd / 3rd supervisor for 1 Full-Time 0 Part-Time UK university candidates
Previously supervised 7 UK university/CNAA candidates (successfully completed supervision)

6.3 Third Supervisor, if applicable *(include name, qualifications, post held and place of work):*

N/A

Currently supervising as Director of Studies.............. Full-Time................ Part-Time UK university candidates

* delete as appropriate

Currently registered as 2nd / 3rd supervisor for........... Full-Time................ Part-Time UK university candidates
Previously supervised . . . . UK university/CNAA candidates (successfully completed supervision)

6.4 Details of any other person(s) who will act in an advisory capacity *(name, qualifications, post held and place of work):*

N/A

7. Period of time for Completion of Programme of Work (see Regulations G5.1 and 5.2)

7.1 Expected starting date for registration purposes: 03/10/2016

7.2 Amount of time (hours per week average) allowed for programme (see Regulation G4.6): 35+

7.3 Expected duration of programme (in years) on the above basis to MPhil: 1 and additionally to PhD:2
(see Regulation G5.1)

8. Statement by the Applicant

I wish to apply for registration for the degree of MPhil with the possibility of transfer to PhD, on the basis of the proposals given in this application.

I confirm that the particulars given in Section 1 are correct.

I understand that, except with the specific permission of LJMU, I may not, during the period of my registration, be a candidate for another award of LJMU or any other University.

I understand that, except with the specific permission of LJMU, I must prepare and defend my thesis in English.

Signed Date
(Applicant)

9. Recommendation by the Supervisors

We support this application and believe that this applicant has the potential to complete successfully the programme of work proposed.

We recommend that this applicant be registered as a candidate for an LJMU research degree.

Signed Date
(Director of Studies)

Signed Date
(Second Supervisor)

Signed Date
(Third Supervisor - if applicable)

10. Recommendation by the School

I support this application for registration as a candidate for a research degree of LJMU. I am satisfied that the necessary resources are available and that adequate facilities will be provided to enable the applicant to conduct and complete the research programme in an efficient and safe manner.

Signed Date
(Director of School)

* delete as appropriate

11. Recommendation by the Faculty Research Committee

This application has been approved on behalf of the Faculty Research Committee.

Signed Date
(Chair of Faculty Research Committee or nominee)

* delete as appropriate