

APPLICATION FOR RESEARCH PROGRAMME APPROVAL

This form must be completed electronically and signed by all parties. Please insert answers in the grey boxes or click on choose an item to select from the drop down lists available.

Please note that the Doctoral Academy is unable to accept handwritten, incomplete or unsigned applications.

All documents including appendices must be submitted as one PDF document with appendices attached in the order listed at the end of the form.

SECTION 1 – APPLICANT'S PERSONAL DETAILS**Student ID No:** 816460**Date of Birth (dd/mm/yy):** 19/01/95**Surname:** Lisboa-Wright**Gender:** **Forename(s):** Alexander Hugo Fernando**Term time address:** Flat 36 Room 3, Liberty Atlantic Point, Naylor St, Liverpool, L3 6LS**Present post and place of work (if applicable):** PhD Student, Astrophysics Research Institute, Liverpool John Moores University**SECTION 2- QUALIFICATIONS, TRAINING AND EXPERIENCE****Qualifications** *(please include details of higher education qualifications only):*

Name of awarding body: The University of Manchester

Course completed: MPhys(Hons) in Physics

Full title of award as stated on degree certificate: Master of Physics in Physics

Classification of award: First-class honours

Date of award (dd/mm/yy):

11/07/17

Name of awarding body:

Course completed:

Full title of award as stated on degree certificate:

Classification of award:

Date of award (dd/mm/yy):

Previous training and experience

Please include details of activities (with dates) relevant to this application, and of any research or other relevant papers, books, etc which have been published.

If you are applying to register for PhD direct please provide details confirming that your Masters' degree is in a discipline which is appropriate to the proposed research and that it included training in research and that it included training in research and the execution of a research project.

Academic Referees *(please include the names and addresses of two external referees, if applicable):*

SECTION 3 – FUNDING AND RESOURCES

Who is paying your tuition fees:

If externally or match funded please provide the name of your external sponsor:

Science & Technology Facilities Council (STFC)

SECTION 4 – RESEARCH PROGRAMME DETAILS

Faculty and School/Department or Research Institute:

Mode of Study:

Start date (dd/mm/yy): 02/10/17

I wish to register for the degree of:

Are you transferring your research degree award from another academic institution?

If yes please attach a letter from your previous academic institution confirming details of your previous registration and that you have withdrawn from the programme at Appendix 1.

Anticipated completion date(dd/mm/yy): 02/10/21

Proposed title of the research programme:

Rotation & levitation in stellar evolution modelling

Aims of the research programme:

Proposed plan of work: *Please attach at Appendix 2 a copy of your proposed plan of work which must be no more than 4-6 pages long in Arial font / point 12. The plan should identify your proposed research questions, set out the research context, outline your methodology and clearly state how the work is original. You should arrange your plan under the following headings:*

- 1. Background and relationship to previous work;*
- 2. Outline of research area and key questions;*
- 3. How the research contributes to knowledge in the field;*
- 4. Proposed Methodology (how you plan to undertake the work).*

This must be accompanied by the following documents:

A single page time-plan for the project (Gantt chart or similar) setting out your key research milestones to show feasibility of the programme within the appropriate registration period.

A bibliographical list of recent key academic references which details the leading research in the field.

Please confirm that all the facilities, equipment and funding required for the investigation, including overhead costs and consumables are available.

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If no, please explain what arrangements / contingencies are in place to address this:

Collaborating Establishment (if applicable)

Please insert name of collaborating establishment and append a letter of support from the collaborating establishment to LJMU setting out the agreed arrangements between the 2 institutions at Appendix 3:

Relationship between work to be undertaken in the collaborating establishment and that to be undertaken at LJMU or elsewhere

Are you registering under a formally approved collaborative award agreement between LJMU and another academic institution?

If yes, please state the name of the other academic institution here:

Ethical Approval

Is ethical approval required?

If ethical approval is required please confirm the stage(s) when it will be required (month(s)/year(s) to be inserted):

SECTION 5 – TRAINING AND SKILLS DEVELOPMENT

Research Student Induction *(please confirm if you have attended the Research Student Induction organised by the Doctoral Academy):*

Research Ethics Training *(please append a copy of your 'certificate of engagement' to confirm that you have completed the Introduction to Research Ethics training module on Blackboard at Appendix 4)*

Training Needs Analysis *(please confirm if you have completed a training needs analysis in conjunction with your Director of Studies):*

Training and development requirements (*please insert details of the agreed training and development opportunities identified*):

Integrated programme of study (*where such a programme is proposed details of the course of postgraduate study on which the candidate's performance is to be formally assessed are required*):

SECTION 6 – SUPERVISION ARRANGEMENTS

Please note that attendance at Research Supervisors' Workshop is a requirement for all supervisors who are new to research degree supervision and/or new to supervision of LJMU postgraduate research students.

Director of Studies

Name: Professor Maurizio Salaris
Qualifications: PhD
Current post: Professor of Stellar Astrophysics
Place of work: Astrophysics Research Institute, LJMU

Experience of supervision of registered UK university research degree candidates:

Currently supervising as Director of Studies: Full Time: 2 Part-Time: 1

Currently registered as 2nd/3rd supervisor for: Full Time: 1 Part-Time: 0

Successfully completed supervision:

Previously supervised: 10 UK university PhD candidates:

Previously supervised: 0 UK university MPhil candidates:

Second Supervisor

Name: Professor Nathan Bastian
Qualifications: PhD
Current post: Director of Research
Place of work: Astrophysics Research Institute, LJMU

Experience of supervision of registered UK university research degree candidates:

Currently supervising as Director of Studies: Full Time: 1 Part-Time: 0

Currently registered as 2nd/3rd supervisor for: Full Time: 4 Part-Time: 0

Successfully completed supervision:

Previously supervised: 2 UK university PhD candidates:

Previously supervised: 3 UK university MPhil candidates:

Third Supervisor (if applicable)

Name: Dr. Steve Longmore

Qualifications: PhD

Current post: Reader in Astrophysics

Place of work: Astrophysics Research Institute, LJMU

Experience of supervision of registered UK university research degree candidates:

Currently supervising as Director of Studies: Full Time: 5 Part-Time: 0

Currently registered as 2nd/3rd supervisor for: Full Time: 1 Part-Time: 0

Successfully completed supervision:

Previously supervised: 1 UK university PhD candidates:

Previously supervised: 0 UK university MPhil candidates:

Advisors (please provide details of any other person(s) who will act in an advisory capacity)

First Advisor (if applicable)

Name:

Qualifications:

Current post:

Place of work:

Second Advisor (if applicable)

Name:

Qualifications:

Current post:

Place of work:

A completed and signed RD41 must be attached at Appendix 5 for any proposed external supervisor(s) or advisor(s).

SECTION 7 – BACKDATING STATEMENT

Research degree programme approval is a formal milestone within a student's postgraduate research programme. Faculty Research Degrees Committees hold primary responsibility for reviewing student applications for registration prior to formal approval by the University Research Degrees Committee.

Applications for research degree programme approval are expected to be endorsed by local Faculty Research Degree Committees and submitted to the Doctoral Academy within the following time periods from initial enrolment:

Full-time students – up to 3 months

Part-time students – up to 6 months

Approval of applications received outside the stated normal periods will be at the discretion of the University Research Degrees Committee.

Applications received after these normal periods must be accompanied by a statement from the student's Director of Studies, endorsed by the Faculty RDC which provides an explanation for late submission including the following:

- *Any mitigating factors for the late submission*
- *Evidence that the student is on track to complete their target award within the maximum registration period permitted under the University's Research Degree Regulations*

SECTION 8 – SIGNATURES

Applicant

I wish to apply for registration for the degree of

on the basis of the particulars

given in this application.

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: 10/01/18

Supervision Team

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 (*Director of Studies*):

Date:



Signed (*Second Supervisor*):

Date:

Signed (*Third Supervisor*):

Date:

Director of School/Head of Department or Research Institute

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/Head of Department or Research Institute*)

Recommendation by the Faculty Research Degrees Committee (FRDC)

This application has been considered and approved by the FRDC.

Signed:

Date:

(*Chair of FRDC or other FRDC member in cases where the Chair is a member of the supervision team*)

LIST OF APPENDICES

Appendix 1: Confirmation of withdrawal from previous academic institution (*if applicable*)

Appendix 2: Plan of work including time plan and list of key academic references (*compulsory*)

Background

The theory of stellar evolution has been developed and established during the last sixty years, and its main predictions confirmed by a large number of empirical tests that have involved photometric, spectroscopic and more recently asteroseismic (observations of non-radial stellar pulsations) observations. Results obtained from stellar model computations are nowadays widely used to develop a vast array of techniques to determine distances, ages, star formation histories and chemical evolution of star clusters and galaxies.

The accuracy of results obtained from stellar population analyses is tied to the accuracy of the current generation of theoretical stellar models; in this respect one particularly thorny issue is to model all possible mechanisms that cause transport of chemical elements between different regions within a star. The temporal evolution of the chemical abundance profiles within stars

is their main driver of the star's evolution, and can be in principle tested through spectroscopic observations of surface abundances of key elements, asteroseismic observations (that can test the internal chemical stratification of stars), and more indirectly through the effect on star counts

(sensitive to evolutionary timescales) and evolutionary paths in colour-magnitude-diagrams (CMDs), that are all affected by the internal chemical profiles (see, e.g., Salaris & Cassisi 2005 and references therein).

In recent times, it has become clear that mixing induced by rotation (denoted as rotational mixing), radiative levitation (upward displacement of elements when the acceleration imparted by interactions with photons is larger than the local gravitational acceleration) and thermohaline mixing (instability that arises when a layer of higher molecular weight lies above layers of lower molecular weight in the presence of a gravitational field) need to be included in stellar evolution modelling to explain a number of spectroscopic observations in old stars.

However a self-consistent implementation of all these three processes in stellar evolution codes and the study of their combined effect on the chemical evolution of stars is still lacking.

Stellar evolution codes solve a 1-dimensional (1D) system of differential equations that allow to calculate the run of physical (e.g. luminosity, temperature, density, specific heats) and chemical quantities, from the centre to the surface (photosphere) of a stellar model with a given initial mass and chemical composition, and their evolution with time.

The effect of rotation can be included in 1D codes with a small modification of the equations and reinterpretation of the variables, as described e.g. in the review by Salaris & Cassisi (2017). Rotational mixing can then be treated as a diffusive transport of elements (hence described by a diffusion equation for each chemical species) that basically opposes the formation of chemical gradients within the model.

Thermohaline mixing can also be implemented as a diffusive process (Ulrich 1972, Kippenhahn et al. 1980, Charbonnel & Zahn 2007) with a specific diffusion coefficient that is equal to zero when the conditions for thermohaline instability are not satisfied. Finally,

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mixing due to radiative levitation can also be treated as a diffusive process, with diffusion coefficients derived from accurate calculations of momentum exchange between photons and nuclei (Turcotte et al. 1998).

To date, these three element transport mechanisms have never been included and treated simultaneously in stellar evolution calculations, even though their combined effect on the model chemical profiles is different from what expected when considering them separately. Just as an example, rotational mixing and radiative levitation on their own tend to increase the surface abundance of nitrogen (an important element in the context of stellar evolution) during the longest phase of stellar evolution (the so-called main sequence), but if thermohaline mixing is included, one expects this latter effect to limit or even suppress the surface enhancement caused by rotational mixing and radiative levitation (Deal et al. 2016).

The variation of the chemical profiles caused by these transport processes affects also lifetimes, luminosities and surface temperatures of the models, due to their effect of the nuclear burning (they affect the amount of nuclear fuel to burn) and the temperature/density structure of the models (see, e.g., Salaris & Cassisi 2017 and references therein).

Proposed research

The proposed research involves the self inclusion in an existing stellar evolution code of the mathematical treatment to model the three element transport mechanisms discussed before. Stellar evolution models that include these mechanisms will be then calculated, to address a number of open problems raised by observations of star clusters, as detailed below.

The first and major step is to include rotation and rotational mixing, thermohaline mixing and radiative levitation in the BaSTI stellar evolution code (Pietrinferni et al. 2004), a code that has been developed at the ARI in collaboration with scientists at the Astronomical Observatory of Abruzzo, in Italy. Stellar model calculations performed with this code are routinely used by the wider astrophysical community to interpret observations of stellar populations in the Milky Way and other galaxies.

This task is complex but feasible. The stellar evolution code (written in Fortran, still the standard programming language of computationally intensive astrophysics codes) comprises dozens of subroutines that solve the full system of equations that describes the structure and evolution of a star. The numerical infrastructure to include these additional processes is also in place, in particular the array of diffusion equations to be used to model these additional mechanisms of chemical element transport, and the transport of angular momentum in rotating models.

The implementation will follow a natural progression. The first (and simpler) process to be implemented is thermohaline mixing. The diffusion coefficient by Charbonnel & Zahn (2007) will be employed, with the free parameter calibrated to reproduce the red giant

surface abundances of N and C measured in old stars of the Milky Way (Gratton et al. 2000). These observed abundances depends only on the efficiency of thermohaline mixing, and are the standard benchmark to tune the efficiency of this process.

The implementation of rotation will follow. This will require slightl modifications to the stellar evolution equations, the addition of equations for the calculation of the transport of angular momentum and chemicals. The implementation of these transport mechanisms will follow the diffusive implementation described in Salaris & Cassisi (2017). Models with rotation will be tested against similar calculations of other groups (Ekstroem et al. 2012, Choi et al. 2016).

Finally, radiative levitation will be implemented. The routines to calculate radiative accelerations on the ions are freely available (Seaton 2005), and will be included in the code and used to calculate the appropriate diffusion coefficients for each elements. Tests of models with radiative levitation will be made by comparing with independent results from Turcotte et al. (1998).

When all these three mechanisms are in place, specific calculations will be performed to address the following three sets of astrophysical observations.

Extended turn off regions in CMDs of young star clusters

A large fraction of studied massive stellar clusters in the Large Magellanic Cloud galaxy host stellar populations that display CMDs with a spread of luminosities and colours in main-sequence turn-off stars (stars at the end of the main sequence phase before they expand to become red giants) that cannot be explained by photometric errors or stellar binarity (e.g. Bastian et al. 2016). These phenomenon, often associated to multiple main sequences, are difficult to intepret by current theories about star cluster formation. One promising idea is that stars born with different rotation rates are responsible for these effects. If confirmed, this will open new avenue of research regarding the formation and evolution of massive star clusters, with potential links to the past evolution of the old globular clusters we see today in our galaxies and external galaxies. This idea will be tested with dedicated calculations of rotating and non-rotating stellar models, compared to observed CMDs of young massive clusters with extended turn off regions. Confirmation or rejection of this scenario will provide an important step forward in our understanding of the formation of these astronomical objects.

Surface abundances of turn off stars in globular clusters

Globular clusters are systems made of a few hundred of thousand stars, orbiting the halo of galaxies, formed right after the Big Bang. The study of globular clusters provides crucial information about the early stages of galaxy formation. One major puzzle in globular cluster studies is to explain the surface abundance pattern of stars at the turn-off (e.g. Korn et al. 2006). No single element transport mechanism can explain the observed abundances, but it is widely recognized that a combination of levitation, rotation and

possibly thermohaline mixing is probably the culprit. This issue will be addressed with new calculations, once all these three mechanisms are consistently included in the BaSTI stellar evolution code.

Surface abundances of hot horizontal branch stars in globular clusters

The same kind of problem shown by turn off stars appears also in hot horizontal branch stars hosted by globular clusters. These stars are in a later evolutionary phase compared to the main sequence, producing nuclear energy by transforming He into C and O. Spectroscopy reveals a surface abundance pattern so far unexplained (Behr et al. 2000), but again suspected to arise from the interplay between levitation, rotation and possibly thermohaline mixing. Appropriate stellar model calculations will be performed to address this issue and test whether the interaction amongst these three element transport mechanisms is able to reproduce the observations.

Impact

The results of the proposed work is predicted to have a major impact on our understanding of the surface chemical evolution of stars, as well on scenarios for the formation of massive star clusters. They will be published in peer-reviewed astrophysics journals, presented at conferences and public talks.

Timeline

October 2017 – December 2017

Literature review, visit to Osservatorio Astronomico d'Abruzzo to be introduced to the latest version of the BaSTI code

January 2018 – June 2018

Submission of RD9R. Implementation of thermohaline mixing in the stellar evolution code, tests, comparisons with independent calculations, calibration of the diffusion efficiency coefficient

July 2018 – September 2018

Implementation rotation in the stellar evolution code

Write up and submission transfer report

October 2018 – February 2019

Continuation implementation of rotation, tests, comparison with independent calculations

March 2019 – July 2019

Calculation of models to study extended turn off phenomenon, comparison with observed CMDs, write up and submission paper about this study

Aug. 2019 – Dec. 2019

Implementation radiative levitation in the stellar evolution code, tests and comparisons with independent calculations

Jan. 2020 – May 2020

Calculation of models with rotation, levitation and thermohaline mixing for globular cluster turn off and horizontal branch stars. Comparisons to observations

Write up and submission of two papers about this study

July 2010-September 2020
Write up and submission PhD thesis

References

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Appendix 3: Letter(s) of support from collaborating establishment(s) (if applicable)



Appendix 4: Introduction to research ethics training certificate of engagement
(compulsory on-line training)



Appendix 5: Completed and signed form RD41 for any proposed external supervisors or advisors (if applicable)

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