September 17, 2015

EXAMINER'S REPORT

on the PhD thesis entitled

Neutron-Capture Nucleosynthesis and the Chemical Evolution of Globular Clusters

by **L.J. Shingles**

This thesis covers the subject of element genesis in stars of low and intermediate mass ($\approx 1 - 8 M_{\odot}$), which encounter the phase of unstable double-shell burning, the so-called *Thermally pulsing Asymptotic Giant Stars*. The general physics of such stars, their structure and detailed evolution can be modelled theoretically only with a large number of simplifying assumptions and under severe computational problems. Numerical models are the only way to assess the details of their interior processes. They are characterized by a large number of different physical effects which strongly interact with each others, such that a separation of processes is not viable. The computations are difficult and resource intensive and require a high level of expertise, both in numerics and in stellar and nuclear astrophysics, to be performed successfully.

At the same time are these stars significant sources of newly created chemical elements, in particular those of high nuclear charge, which are, among others, crucial for biological processes and technology.

The thesis is therefore concerned with an important subject of on-going interest, on which several, but not too many groups in the international community are working. It covers mainly three aspects of the general problem of nucleosynthesis in *Asymptotic Giant Branch* (AGB) stars:

1. An anomalously low sulfur abundance in observed Planetary Nebulae (one of the end products of AGB stars). The question investigated here (Chapter 2) is, whether this could be the result of s-process nucleosynthesis in AGB stars, and if so, under which specific conditions this could happen. The hope is to learn about the details of the s-process (a neutron-capture process specific in AGB stars for the creation of very heavy elements).

2. The difference in s-process element abundance distribution between two Globular Clusters (Chapter 3). One (M4) is very homogeneous in its iron-peak element abundances, as is normal for Globular Clusters, the other (M22) is showing two different populations in this respect. The question addressed is whether the different s-process element distributions can be explained by current AGB models and internal chemical evolution.

3. A new set of AGB models which covers the nucleosynthesis of helium-enriched stars (Chapter 4). Such stars are indicated by specific properties of Globular Clusters, but their evolution has not been investigated so far for a broad range of metallicities and masses.

From this list it is evident that all parts of the thesis are concerned with the same underlying astrophysical problem and therefore the thesis is internally very consistent. For all three parts the candidate has used the same stellar evolution program that was available to him, including the internal nuclear network and a post-processing network for the nucleosynthesis of elements and isotopes not relevant energetically for the evolution. Mastering such a program and running successfully a large number of AGB-evolution models, as was done here, is a significant achievement that requires both numerical expertise and a thorough understanding of stellar and nuclear physics. The outcome of the thesis is a very extensive set of element yields (products of the internal nucleosynthesis returned to the galactic chemical evolution) and stellar surface abundances for a variety of stellar and physical parameters. These results, in comparison with observations, allow conclusions about the ill-determined internal processes in AGB-stars, such as the details of mixing between envelope and nuclear burning regions (e.g. the often mentioned ^{13}C-pocket, a pre-requisite for the s-process). The results are in detail listed in the appendix of the thesis.

In addition to the existing programs, the candidate has developed his own chemical evolution program (also explicitly listed in an appendix). Although this model is rather simplistic in comparison with other such programs for the chemical evolution of the galaxy, it is a very appropriate tool and very useful for the internal chemical evolution of globular clusters. It has been verified with comparisons to another program of the same kind. It employs both published yields for rotating massive stars as the new AGB yields obtained in this thesis.

Each of the three chapters listed above all corresponds to a scientific paper. All of them have been published in fully refereed astronomical journals of the highest international standard (this includes also the content of Chapter 4, which, at the time of thesis submission, was accepted but not yet printed). This underlines the importance and relevance of the work done. For all three chapters the candidate has convincingly described his own contribution, which in all cases can be considered as being the dominant one in comparison to those of his co-authors. Therefore all three chapters are very appropriately included in this thesis.

In each chapter a first section preludes the content of the published paper, giving a summary of the problem and connecting the content with the general frame of the thesis. Although these summaries are identical to the published paper abstracts, they are very well suited for this purpose. Thus the whole thesis is very homogeneously embedded into the grand theme of AGB nucleosynthesis.

The introduction is an excellent piece of work. It introduces all aspects of the thesis, from the origins of the elements in the Big Bang and in stars, to details of stellar evolution and nucleosynthesis, to the specifics of the s-process in AGB stars, and to chemical evolution and properties of Globular Clusters. The literature quoted is covering both seminal historical as well as current papers. This chapter is convincing evidence of the fact that Mr Shingles has successfully mastered his field in a wide context. It is, as are the other chapters, written in a very eloquent and smooth fashion, can be easily read, and contains all details without tiring the reader.

The second chapter added to the published papers is the one about the conclusions (Chapter 5). This is a bit short (two pages of a summary of contents, and one page of "future directions"), but summarizes nicely what was achieved: From Chapter 2 it is learned that the sulfur anomaly cannot be reproduced by nucleosynthesis in current AGB models. In fact it appears unlikely that it is created solely in this phase. However, a new technique to constrain the size of the ^{13}C-pocket was found as a side product of the simulations. This may prove to be valuable for other investigations.

The models of Chapter 3 provide clues to the internal chemical evolution of Globular Clusters, and also independent evidence for the age difference of the two M22 populations.

Chapter 4 constitutes the first library of stellar models and chemical yields for He-enhanced AGB stars. It will set the standard for similar models by other groups and fills a gap in available models which are needed for the interpretation of sub-populations of Globular Clusters.

In total, this thesis covers many relevant aspects of AGB evolution. It uses up-to-date tools, partially developed by the candidate, and presents new and interesting results. The content is fully appropriate for a PhD in astrophysics and satisfies all requirements of being of international standard. Therefore the Doctor of Philosophy should be awarded to Mr Shingles.

A few minor corrections would be required:

1. page 6, equation (1.6): the right hand side corresponds to the inverse of the left hand side!
2. page 8, beginning of Sect. 1.4.3: the peak in the binding energy per nucleon as the main reason for the end of hydrostatic nuclear fusion in stars is lacking from the argumentation and should be added.

PHD Thesis on *"Neutron Capture Nucleosynthesis and the chemical evolution of Globular Clusters"* presented by Luke Jeremy Shingles: Examiner's report.

This thesis is a collection of three works made by the candidate in collaboration with his supervisor and other researchers. Three articles have been already published in refereed journals (two on the *Monthly Notices of the Royal Astronomical Society* and one on the *Astrophysical Journal*). All regard the nucleosynthesis in Asymptotic Giant Branch (AGB) stars and deal with various open problems of the theoretical calculations of the chemical yields of these stars, with particular emphasis to the neutron capture nucleosynthesis. The first work concerns the origin of the sulphur depletion observed in some planetary nebulae, likely the daughter of low-mass AGB stars. Although the author of the thesis cannot provide a viable solution of this problem, his investigation allows to exclude some of the previously proposed solution. In particular, the uncertainties of key nuclear reaction rates, i.e., the main neutron sources and some neutron capture reactions, are discussed and their effects on the nucleosynthesis are illustrated in some details. The second work deals with the intriguing question of the heavy elements overabundances observed in some stellar components of Galactic Globular Clusters. Yields from stellar models of intermediate and massive stars are combined to estimate the expected chemical enrichment of the pristine material of the galactic halo from which these stellar clusters were formed. This work confirms previous claims, e.g, that the star formation period lasted a few hundred million years in clusters showing overabundances of heavy elements synthesized by the slow-neutron-capture process (s-process). The third work provides, for the first time, a detailed study of the evolution and nucleosynthesis of intermediate mass stars with an anomalous large amount of He (up to Y=0.40) in their initial composition. This investigation is motivated by the possibility recently advanced that some Globular Clusters may host stellar populations characterized by such a peculiar chemical composition.

Although most of the theoretical calculations have been done by means of computer codes developed by other researcher (the stellar evolution code and the post-process nucleosynthesis code, in particular), a valuable contribution of the candidate is clearly recognized in the production of a chemical evolution code (Evel ChemEvol; the source code is attached in the appendix to the thesis). It is suitable to study relatively simple stellar systems and it has been successfully used to model the early pollution of the gas in Globular Clusters forming regions. In any case, it must be noted that in his investigation of the chemical peculiarities of Globular Clusters and Planetary Nebulae, the candidate makes an appropriate and compelling use of the stellar model results.

As a whole, the candidate demonstrates a good knowledge of the subjects faced in his thesis. He accurately discusses the extant literature and the major open problems looking for a solution.

The thesis is definitely well written. I appreciate, in particular, the introduction to each chapter which provide a clear presentation of the scientific framework. The comprehension, even for a non-expert, is generally very good. Methods and results are also clearly illustrated.

No revisions of the thesis are required. In my opinion, the candidate should be granted the award of Doctor of Philosophy.

Luke Shingles: Neutron capture nucleosynthesis and the chemical evolution of globular clusters

The thesis addresses the problem of the enrichment of the interstellar and circumstellar medium by the products of stellar nucleosynthesis. The enrichment is an intricate problem, combining nuclear reactions with often uncertain reaction rates, convection and diffusion affecting local conditions and elemental abundances, episodic dredge up to the stellar surface, and finally stellar mass loss. There are many uncertainties in the overall process. The current thesis uses observed elemental abundances to constrain nuclear reactions and interior conditions. The stellar model which is used is an existing one, where some parameters are adjusted in the research. The student has written a chemical evolution code to study stellar populations.

The brief introduction shows an excellent understanding of the problem and methodology. All required aspects are covered well. There are some minor gripes with figure in this chapter: Fig 1.2 is stated to show the r and s process when in fact it mentions the r and p process only, Fig. 1.4 has a different layout than stated in the caption, and Fig. 1.7 lacks units on the vertical axis.

Chapter 2 addresses the problem that measured sulfur abundances in stellar ejecta are much lower than predicted. The student attempts to induce sulfur destruction through an s process in the models. The conclusion is that this is not possible with any of the attempted model adjustments. This argues strongly that the problem is an observational one. The only lacking aspect is that the predicted abundance of chlorine (product of the proposed sulfur reaction) is not compared to observations.

Chapter 3 compares the s process enrichment in two different globular clusters, by calculating yields of different masses and rotation rates. There is an excellent overview of the recent literature. The chemical evolution code is used to derive an age range for the enrichment of 300 million years. This is a plausible result although with the model uncertainties it may not be a unique solution.

Chapter 4 investigates yields from stars with enhanced helium abundance. This is an issue for stars in globular clusters where a helium rich sequence has been found. The calculations are very useful, not just for the yields but also to help identify the helium rich population among the evolved stars. It is not entirely clear whether a population of stars will exist which incorporates these yields, as it depends on enrichment and star formation time scales.

The work shows a good understanding of the science and the details of the models. All three chapters have been published in the main scientific journals and easily reach the required standard. The writing is of high standard throughout. Apart from a minor deficiency in some figures in the introduction, no changes are required for the award of a PhD.