Final Report- LIMBS - 220440

Summary description of the project objectives

The *Low- and Intermediate-mass Binary Stars – LIMBS* – project seeks to better understand the physical processes at play in interacting low- and intermediate-mass binary stars. The primary objective is to develop a computational framework to calculate in detail the evolution of these stars. A good explanation of the physics at work in binary stars is crucial to solving many important questions in 21st century astrophysics. Most importantly perhaps is the discovery that the Universe is accelerating its expansion, a result obtained through the study of Type Ia supernovae which originate in binary stars. Unfortunately, our knowledge of binary-star physics is rudimentary at present: we still do not know which binary stars can explode as Ia supernovae!

One of the ways to better understand binary stars is to look at the result of their evolution. In particular the *LIMBS* project seeks to better explain the evolution of chemically peculiar stars such as the barium stars. These are peculiar in the sense that, as their name suggests, they are rich in the chemical element barium. However, they are at a stage of their evolution when they should not have made any barium. Instead it was made by a companion star and transferred onto the star we see today through accretion of a stellar wind. Qualitatively the general picture is well appreciated, but quantitively it is not. The barium stars have many properties which are cannot be explained: why are they eccentric when canonical tidal theory says they should be circular? Why do they not form in binary systems with periods longer than a few decades? How do short (100 day) period barium stars form? These questions are linked to many others in stellar physics, in particular the efficiency of chemical mixing, and are intimately connected to the origin of some of the oldest stars in our Galaxy, in particular carbon-rich extremely-metal poor stars which should form by a similar physical process.

The *LIMBS* project aims to build on existing expertise in single-star evolution at the Institute of Astronomy and Astrophysics at l'Université Libre de Bruxelles in order to construct a detailed model for binary star evolution so we can work out how chemically peculiar stars, like the barium stars, form. For many years the *STAREVOL* stellar-evolution code has been used to successfully model the evolution of the most complicated phases in stellar evolution of low- and intermediate-mass single stars. Through the *LIMBS* project the new *BINSTAR* code has been constructed. It is based on *STAREVOL* so contains many of the its features such as its state-of-the-art physics package (opacity, equation of state, nuclear network, numerical solvers). *BINSTAR* has been extended to self-consistently follow the evolution of both stars in a binary system. It includes new physics such as mass transfer by both stellar wind accretion and Roche-lobe overflow, stellar tides and models the evolution of the binary orbital parameters, namely the separation and eccentricity.

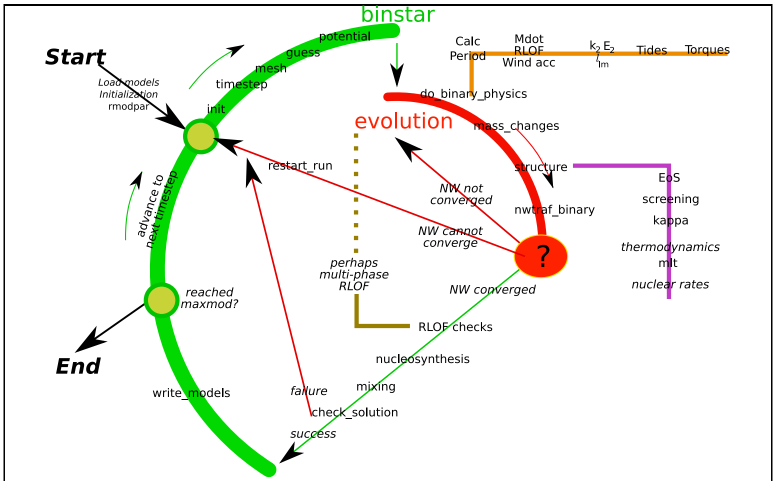
Description of the work performed

The first objective was to clean up the existing (as of 2008) code and modernise it by using the latest version of the programming language (FORTRAN). The process was automated, to reduce the number of inevitable errors when converting such a large collection of code. After this process the code was more modular and ready for the following phase of development. The next objective was to redesign the structure of the code so that it would run two stars simultaneously. This involved a considerable amount of logistical effort to make sure the stars behaved correctly and much time was necessarily spent testing the results against equivalent single-star runs. Many of the run-time bottlenecks, such as calculated of the equation of state and nucleosynthesis, were parallelised in order to make use of the latest multi-core computer technology.

The next part of the project was to introduce binary-star physics to *BINSTAR*. Given the now modular nature of the code, implementation of the orbital dynamics and simple mass transfer between the stars was relatively simple. However, some effort was required to convert the numerical solution scheme (the Henyey method) to enable it to work efficiently for two stars together with the inclusion of the binary-star interactions. A self-consistent scheme for mass-transfer by Roche-lobe overflow was developed for radiative stars. Wind accretion by the Bondi-Hoyle mechanism was included. The results of the new *BINSTAR* code were tested against my rapid stellar evolution code binary_c and found to be similar.

The final stage of development of *BINSTAR* was the inclusion of a self-consistent model for angular momentum and tides. Recent advances in stellar evolution have showed that a detailed treatment of angular momentum is absolutely necessary in order to describe the evolution of many stars and phenomena such as the elusive gamma-ray bursts. This part of the project was more time consuming that was expected for a number of reasons. First, numerous technical problems plagued the self-consistent transport of angular momentum in the stars. These problems have now been resolved. Second, it was hoped that inclusion of the latest tidal-mixing prescriptions, which deal with both angular momentum and chemical mixing due to tides, would have been possible. These proved to be too technically complicated and could not be implemented in the time available. Instead an older formalism was included, which while not so comprehensive still includes the basic physics necessary to model tidal interactions and hence the evolution of stellar spins and orbital parameters such as the eccentricity. Despite this, the tidal interaction formalism implemented in *BINSTAR* represents the state-of-the-art and as such is a considerable step forward in our ability to model interacting binary-star systems.

In conclusion, the LIMBS project has delivered its primary objective, the development of a new, self-consistent, detailed binary-stellar evolution code, *BINSTAR*. This has laid the foundation for a programme on detailed modelling of binary stars at the Institute of Astronomy and Astrophysics (IAA) at l'Université Libre de Bruxelles (ULB) which will continue well into the next decade. Already a new post-doctoral researcher has picked up where this project left off and is using *BINSTAR* to construct models of chemically peculiar stars.



Flow diagram showing how the 2010 version of BINSTAR functions.

In parallel to the development *BINSTAR* I used my existing binary-star population synthesis code *binary_c* to work on experimental models which describe the formation and orbital characteristics – in particular the odd eccentricity – of the barium stars. This approach cannot provide the detailed analysis of *BINSTAR*, but is a critical step in evaluating which binary systems *BINSTAR* should try to model. It also fulfils one of the aims of the LIMBS project, a critical, quantitative comparison with observations of barium stars which include new observations from the group at the IAA. This is because *binary_c* uses more approximate physics so can be run millions of times faster, hence the binary-star parameter space can be explored. In particular, new physics was introduced to model the following.

1. White dwarf kicks. A new idea was recently proposed, based on observational evidence in globular clusters, which suggested that white dwarfs are given a kick when they are born. It is possible that these kicks give rise the eccentricity in barium stars. My simulations show that this is indeed the case, however rather extreme angular momentum loss is required in order to justify the lack of existence of long-period barium stars. I performed this work with the help of new HERMES consortium (in particular observers in Brussels and Leuven) observational data on the eccentricity of the longest-period barium stars. This remains a promising scenario for future investigation and I plan to follow it up by collaborating with theoretical groups working on three-dimensional fluid dynamics simulations of mass transfer and observers looking at asymmetric planetary nebulae and stellar ejecta.

2. Circumbinary disks and eccentricity pumping. With Tyl Dermine, a student at ULB, an investigation was started into whether circumbinary disks are a potential source of the eccentricity in barium stars. The first results suggest that circumbinary disks can, in some circumstances, lead to eccentric barium stars. Whether they are made in the right number to accurately populate the eccentricity-period space remains to be seen and is work in progress.

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- The *BINSTAR* website can be found at http://www.astro.ulb.ac.be/~izzard/binstar/.