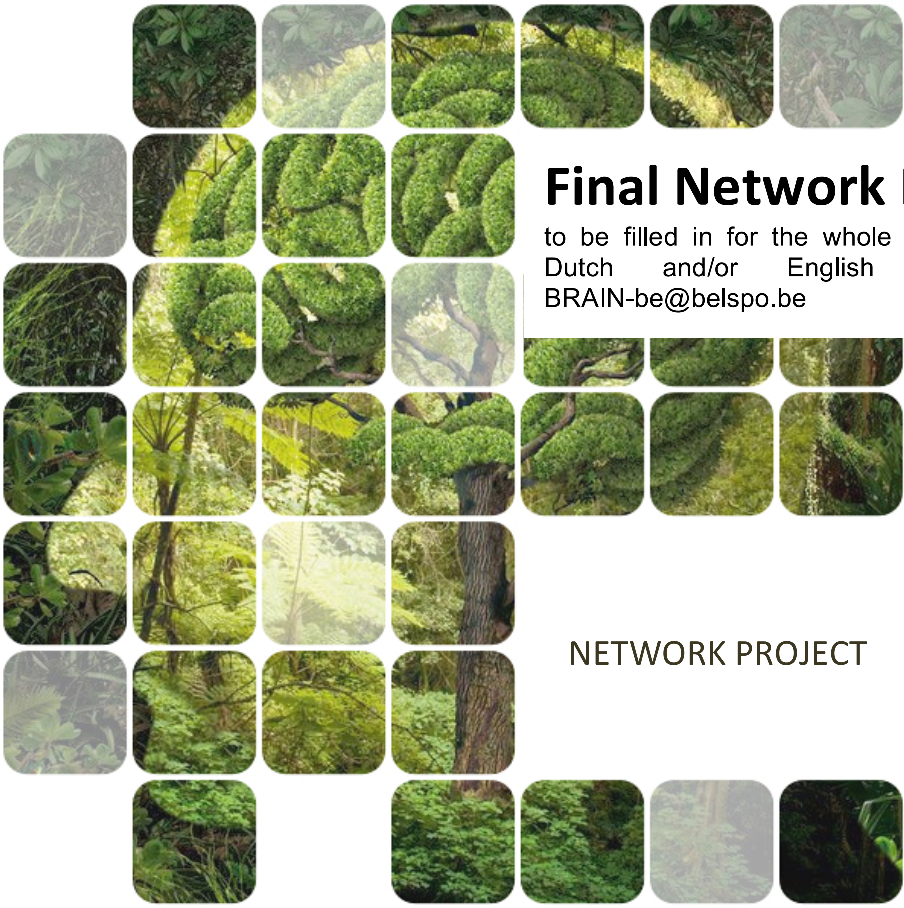

Final Network Report

to be filled in for the whole network in French, Dutch and/or English and sent to BRAIN-be@belspo.be

NETWORK PROJECT

STARLAB

Evolved stars and their shells: Laboratories for stellar physics

Contract - BR/143/A2/STARLAB

FINAL REPORT

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TABLE OF CONTENTS

ABSTRACT

Context. Stars in the mass range 0.8 – 8 Msun (denoted low- and intermediate-mass stars – LIMS – in what follows) dominate the stellar population in our Milky Way Galaxy. During their ascent of the asymptotic giant branch (AGB) phase, LIMS are the siege of a rich nucleosynthesis, forging mainly carbon and elements heavier than iron through the so-called s-process. Because mixing processes bring these elements to their surface, the envelope composition of AGB stars is altered, and some of these stars will turn into carbon stars. As winds disperse the AGB envelope, molecules and dust grains form in a thick shell surrounding the star. As it expands, the circumstellar shell eventually merges with the interstellar medium where it releases the products of the stellar nucleosynthesis, thus contributing to the chemical evolution of the Galaxy.

Some specific families of LIMS are exclusively found among binary systems and the interaction between the stellar components can have a dramatic impact on both the internal structure and the surface chemical composition through the development of mixing processes (e.g thermohaline or rotationally-induced mixing) and exchange of nuclearly processed material between the stellar components.

Although the global evolution of stars is well understood, major uncertainties still affect our understanding of key physical and chemical processes. For instance, major shortcomings remain in the description of convection and internal mixing, mass loss, dust formation and gas-phase reactions in thick circumstellar shells, and, in case of binary systems, mass and angular-momentum transfer between the stellar components.

Objectives. The goal of this project is to boost our understanding of (some of) the physical and chemical processes at work in LIMS. Specifically, we plan

(i) to diagnose nucleosynthesis and mixing in LIMS;

(ii) to uncover the link between the various classes of binaries involving evolved LIMS;

(iii) to find signatures of mass-loss processes and of binary interaction by studying circumstellar matter on different spatial scales.

Results. (i) Abundances of heavy elements have been obtained for a large sample of S stars, and their comparison with model predictions reveal a good agreement, especially in terms of the onset of the third dredge-up on the asymptotic giant branch. The Nb/Zr ratio as a specific nucleosynthesis signature in binary systems has been confirmed. Locating S stars in the Hertzsprung-Russell diagram led to the surprising result that the s-process nucleosynthesis is already active in AGB stars with masses as low as 1 Msun.

(ii) We have obtained a large number (~200) of orbital elements of LIMS post-mass-transfer systems (post-AGB, RV Tau, dwarf and giant Ba, subgiant and giant CH, S), including long-period binaries among central stars of planetary nebulae, which strengthens the link with other families of post-mass-transfer systems like barium systems. Eccentricity - period diagrams reveal common features among all the post-mass-transfer families (like a smaller average eccentricity at a given orbital period), as do their location in the Hertzsprung-Russell diagram.

(iii) We have shown that the knowledge of the circumstellar-shell (CS) geometry is mandatory in order to derive their dust masses in a accurate way (i.e., better than within a factor of 100!). A list of molecular and atomic spectral features has been built from Herschel PACS and SPIRE spectra that will be helpful for diagnosing the physical conditions characterizing the CS of AGB stars.

Conclusions. The trilateral collaboration between the Royal Observatory of Belgium, the KU Leuven and ULB on the topic of low- and intermediate-mass single and binary stars has been very fruitful, leading to three doctoral theses and 36 papers within 4 years. We regret that the new BRAIN-be rules make such trilateral collaborations not possible any longer.

Keywords. Circumstellar shells, abundances and nucleosynthesis, binary systems, mass loss, stellar structure and evolution

1. INTRODUCTION

Stars in the mass range 0.8 – 8 Msun (denoted low- and intermediate-mass stars – LIMS – in what follows) dominate the stellar population in our Milky Way Galaxy. During their ascent of the asymptotic giant branch (AGB) phase, LIMS are the siege of a rich nucleosynthesis, forging mainly carbon and elements heavier than iron through the so-called s-process. Because mixing processes bring these elements to their surface, the envelope composition of AGB stars is altered, and some of these stars will turn into carbon stars. As winds disperse the AGB envelope, molecules and dust grains form in a thick shell surrounding the star. As it expands, the circumstellar shell eventually merges with the interstellar medium where it releases the products of the stellar nucleosynthesis, thus contributing to the chemical evolution of the Galaxy.

Some specific families of LIMS are exclusively found among binary systems and the interaction between the stellar components can have a dramatic impact on both the internal structure and the surface chemical composition through the development of mixing processes (e.g thermohaline or rotationally-induced mixing) and exchange of nuclearly processed material between the stellar components.

Although the global evolution of stars is well understood, major uncertainties still affect our understanding of key physical and chemical processes. For instance, major shortcomings remain in the description of convection and internal mixing, mass loss, dust formation and gas-phase reactions in thick circumstellar shells, and, in case of binary systems, mass and angular-momentum transfer between the stellar components... Moreover, regarding the evolution of binary systems, the suspected evolutionary link between specific classes of low and intermediate mass binaries (hereafter LIMB) like post-AGB stars with dusty discs and barium stars remains to be elucidated.

In the context described above, the goal of this project is to boost our understanding of (some of) the physical and chemical processes at work in LIMS/LIMB.

2. STATE OF THE ART AND OBJECTIVES

2.1 State of the art

Since the STARLAB project has addressed three different topics, we describe the corresponding state of the art and objectives for each of them successively.

WP1: Diagnostics of nucleosynthesis and mixing in stars

Stellar abundance determinations provide powerful diagnostics when applied to late stages of LIMS evolution (i.e., AGB and post-AGB stars), when dredge-up processes in the envelope bring to the surface internal burning products, resulting from on-going or recent, on-site nucleosynthesis, The surface abundances provide valuable information, not only on nucleosynthesis itself, but also on the history of mixing in these stars.

In the field of evolved LIMS stars, a remaining challenge is to understand the surface s-process enrichments, as a function of initial mass, metallicity and luminosity along the AGB, which are related to the conditions of occurrence of the third dredge-up. The s-process in AGB stars is currently modeled by forcing extra-mixing mechanisms to operate at the base of the convective envelope at the time of the third dredge-up (e.g. Goriely & Siess 2004, Herwig 2005). These mechanisms trigger reactions [like $^{12}C(p,\gamma)^{13}N(\beta)^{13}C(\alpha,n)^{16}O$] producing the neutrons required to form the heavy elements (Straniero et al. 1995). Although this scenario has been successful in explaining the surface abundances of many different stars, its modeling is still highly parametric (e.g. Cristallo et al., 2011; Karakas et al., 2010) and some observations remain unexplained. To give only a few examples: (1) at low metallicities, the s-process is predicted to be so efficient as to fully convert Fe into Pb (Van Eck et al., 2001). This inevitably leads to large Pb/Ba ratios, which are not observed in the four post-AGB stars studied so far (De Smedt et al. 2014) (2) the dichotomy between s-process enriched and non-enriched post-AGB stars (Van Winckel et al., 2003) is not understood. The lack of well-determined distances and hence luminosities in the Galactic (solar-neighbourhood) sample hampers, however, an in-depth theoretical evaluation; (3) the s-process enrichment in C-depleted post-AGB stars like V453 Oph (Deroo et al. 2005) cannot be explained because s-process enhancements should go along with C enrichment, which is not the case in this star. Is it an isolated case or are there many such objects? (4) the carbon enrichment as well as the small 12C/13C ratios detected in s-depleted stars like R- or J-type stars is problematic; (5) the relatively low C/O ratios (just above unity) detected in metal-poor carbon stars and their descendants the carbon-rich post-AGB stars contradict the theoretically-expected very high C/O ratios (Masseron et al. 2010; van Aarle et al. 2013); (6) some very old metal-poor objects, which can be seen as the first low-mass stars of the Galaxy, bear diverse chemical signatures which do not easily fit into the simple categories defined at higher metallicities : some low-metallicity stars share for example signatures of the s- and r-processes, the so-called 's+r' stars (e.g. Jonsell et al. 2006), some are N-rich and s-process-rich (Masseron et al. 2006), a combination which is not possible in old (hence low-mass) single stars, where the hot-bottom burning converting C into N is not thought to operate.

WP2 Uncovering the link between the various classes of binaries involving evolved LIMS

This WP has two interconnected aspects, one related to observations (mainly collected by our HERMES spectrograph installed on the Mercator 1.2m telescope) and the other to binary-star modeling through our BINSTAR code (see Sect. 3).

About 50% of all stars are born in binary systems and will eventually interact. The interaction can lead to dramatic outcomes such as Type Ia SNe, which play an essential role in chemical evolution (and cosmology), but also leads to less energetic outcomes such as symbiotic stars, barium and CH stars, post-AGB stars with dusty discs, or carbon-enriched metal-poor (CEMP) stars. All these systems require binary interaction to explain their specific chemical anomalies (like depletion of refractory elements in the case of dusty-disc post-AGB stars, or s-process overabundances for the other classes).

Binary evolution is very complex and faces many problematic and critical issues. For instance, our understanding of mass transfer involving an AGB star is not satisfactory, since binary-evolution models based on standard prescriptions fail to reproduce the eccentricity-period (*e* -- *P*) distributions of (among others) barium and dusty-disc post-AGB stars. Such diagrams are being obtained for various families of LIMS (with a fair degree of completeness, even for the longest-period orbits) thanks to the on-going radial-velocity monitoring done with our HERMES/Mercator spectrograph. An example is shown in Figure 1 hereafter (from Gorlova et al. 2014), obtained after five years of operation of HERMES, which allows to efficiently sample radial velocity time-series of wide binaries. Similar data are obtained for dusty-disc post-AGB systems, dwarf Ba systems, and CEMP systems.

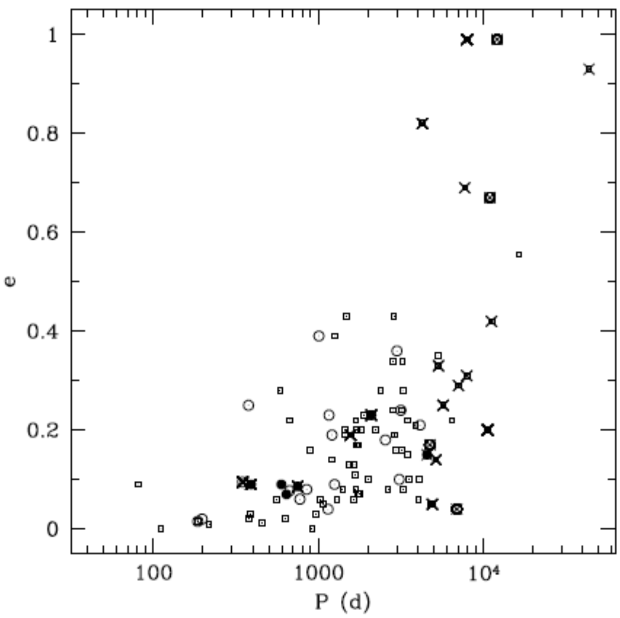

Fig. 1. The eccentricity – period diagram of barium stars (squares) and Tc-poor S stars (circles). The crosses identify those orbits obtained thanks to HERMES data. The black circles denote symbiotic S stars identified from their Hα emission (see Van Eck & Jorissen 2002).

The failure to reproduce these *e* - *P* diagrams demonstrates our poor understanding of

- the accretion efficiency onto the companion (via wind or RLOF), especially in eccentric orbits (where there is phase-modulated accretion),
- the formation of the circumbinary discs observed in post-AGB stars with a specific dusty spectral-energy distribution (e.g. Deroo et al. 2007),
- a possible increase of mass loss prior to Roche lobe overflow (Siess et al. 2014).

WP 3 Circumstellar matter on different spatial scales: signatures of mass-loss processes and of binary interaction

The life cycle of dust and gas in the Universe is one of the main topics in modern astrophysics. Both LIMS, when they are in their final stage of evolution on the AGB, and supernovae are believed to be important contributors of dust and gas to the ISM, although the relative contribution remains uncertain, especially at high redshift (low metallicity).

Mass loss is an important phenomenon of AGB stars and crucial in determining the last phase of LIMS evolution. However, the mass-loss process is still not well understood: what mechanism(s) trigger(s) and drive(s) the mass-loss process, how does it change in time, and with metallicity? The general picture which explains the mass-loss process assumes that stellar pulsations trigger shock waves in the atmosphere. These shocks lift the gas above the stellar surface, creating dense cool layers where microscopic solid particles may form. The radiation pressure exerted by the star accelerates these particles by transmitting momentum through collisions with the gas, dragging them away (e.g. Höfner & Dorfi 1997). In the end, the material escapes from the star and is returned to the interstellar medium (ISM).

The science proposed in this WP addresses some of these questions by studying on the one hand a few objects in great detail using mid-IR data, and on the other hand the more global properties of larger samples of AGB stars in our Galaxy, using Herschel data. In the past decade, our team has built up extensive expertise in this field using advanced international observing facilities combined with state-of-the-art theoretical modeling (see Sect. 3).

Since 2007, the partners are involved in the Herschel Guaranteed Time Key Program MESS ("Mass loss of Evolved StarS", Groenewegen et al. 2011). Besides the three Belgian partners, this is an international collaboration including institutes in Austria, Germany, and the U.K. This project observed a wide variety of evolved stellar objects in spectroscopic and photometric mode in the far-IR using both the PACS and SPIRE instruments. The MESS program has already led to some key papers. For example, Cox et al. (2012) who summarize all PACS imaging data of almost 40 AGB stars to reveal the often very complex morphology of the circumstellar envelopes (CSEs), in contradiction to the paradigm that the CSEs around AGB stars are mostly spherically symmetric. Hydrodynamical simulations are being performed to understand these shapes, taking into account dust (van Marle et al. 2011), and the role of magnetic fields (van Marle et al. 2014). In a few cases the morphology is directly related to binary interaction and this has been studied in Jorissen et al. (2011) and Mayer et al. (2011, 2013), providing the link to WP2. Other key results describe the discovery of multiple shells around the archetypical AGB/carbon-star CW Leo (Decin et al.

2011) and the very first *Nature* paper based on Herschel results (Decin et al. 2010) discussing the discovery of many water lines in this object.

The MESS imaging program focused predominantly on the circumstellar matter *per se,* while the research that is proposed here concentrates on the relation between the central star, the inner part of the CSE where the dust is formed and the acceleration of the wind occurs, with the outer parts of the CSE.

The work on interferometry builds on the expertise that was gained during the last few years thanks to the guaranteed time (about 160 nights in the period 2005-2013) Belgium had on the VLTI Sub Array (VISA). The goal of this part of our study is to quantify the temporal behaviour of the photosphere and the molecular layers around LPVs. First results are presented in Hillen et al. (2010) and Paladini et al. (2011).

The ESO VLTI large programme is led by P.I. Claudia Paladini (ULB), with co-investigators from KULeuven, ROB, and ULB. In this program, Herschel data have been used to select a sample of 15 AGB stars that were observed with MIDI in the mid-IR. Thanks to its high angular resolution, mid-infrared interferometry is able to probe regions ranging from the dust formation zone to the innermost region of the dusty environment (about 3 to 25 stellar radii) where the dynamic processes of shock waves, stellar winds, and mass loss develop. Therefore, the use of MIDI through different baseline orientations gives direct information on the morphology of the very inner part of the dust shell.

2.2 Objectives

The goals of WP1 are

i. to identify the necessary conditions for the occurrence of the dredge-ups and mixing processes needed to produce s-process elements and to bring them to the surface.

ii. to characterize the properties of the s-process nucleosynthesis (efficiency and temperature) as a function of metallicity. This may be done using specific unstable nuclei (like Tc or ^{93}Zr) or their beta-decay product like Nb (Neyskens et al. 2011, Neyskens 2013), and hs/ls or vhs/ls ratios (where vhs denotes any element belonging to the third s-process abundance peak – like Pb – , hs denotes any element belonging to the second peak – like Ba – , and ls denotes any element belonging to the first peak – like Sr –).

iii. to clarify the evolutionary link between AGBs and post-AGBs, by comparing all available observational constraints (abundances, orbital elements, luminosities).

The first two items provide constraints to be met by detailed models of s-process nucleosynthesis in AGB stars.

The aim of WP2 is threefold:

(i) to identify the binary-evolution channel leading to specific families of LIMS binaries like dusty-disc post-AGB systems, dwarf Ba stars and giant Ba stars;

(ii) as a corollary to (i), to understand how these various families are linked to each other;

(iii) to confront the abundance pattern at the surface of these LIMS binaries with predicted abundances.

The aims of WP3 are :

(i) to achieve an in-depth understanding of the effects shaping the outflows around evolved stars, by studying the morphology on the smallest spatial scales through analysis of mid-IR interferometric data.

(ii) to study the overall mass-loss process, dust composition and structure of the CSE from analysis of Herschel PACS and SPIRE spectra. This is obviously connected to the first aim, but uses data at longer wavelengths, and at larger, even global, spatial scales.

3. METHODOLOGY

The resolution of major issues in stellar physics requires a fruitful interplay between data acquisition and reduction methods on one hand, and advanced modeling efforts on the other hand, with strong interactions and feedback between both. That is what we wanted to achieve within this project, building on the strengths of the different partners involved.

In the following, we describe the different phases of processing required for this project. This includes (i) data acquisition and reduction methods, (ii) the determination of the stellar parameters and abundances and (iii) the model predictions.

(i) Data acquisition and reduction methods

The present project relies on multi-wavelength data sets: HERMES/Mercator (Raskin et al. 2011) and UVES/VLT in the optical domain, PIONIER/VLTI in the infrared, and Herschel in the far infrared. Each data set has its own reduction pipeline. The team members have expertise with the specific pipelines required to reduce these data, as some actually contributed to building them (in the case of HERMES/Mercator or Herschel/PACS).

(ii) Codes for deriving stellar / circumstellar parameters and abundance determinations

These methods are needed to extract information from the reduced data, in particular to derive abundances from the observed spectra. The code TURBOSPECTRUM (Alvarez & Plez 1998) used by the partners solves the radiative-transfer equations for a given thermal structure of the stellar atmosphere that is provided by the MARCS models, best suited for late spectral types (as most evolved LIMS have). Appropriate atomic and molecular line lists are needed as well. These may be obtained from the VALD (Kupka et al., 1999) or NIST databases. We also use the BACCHUS code (Merle et al. 2014), which allows to derive automatically the atmospheric parameters and abundances of late-type stars (F, G and K spectral types).

We will also use the MoD (More of DUSTY) and RADMC-3D codes to solve the radiative-transfer equations in a circumstellar shell with dust grains and/or molecular species.

Finally, we have tools to derive spectroscopic orbital elements from a set of radial velocities.

(iii) Model predictions

These methods are used to perform ab initio predictions of

a. stellar structure and evolution, as done by the STAREVOL code. Surface abundances are obtained consistently since STAREVOL includes prescriptions for mixing and nucleosynthesis.

b. orbital evolution of binary systems, as done by the BINSTAR code. This code duplicates STAREVOL for the calculation of the internal stellar structures, and includes the physics associated with tidal interaction, as well as mass and angular-momentum transfer. Similarly to STAREVOL, surface abundances may be predicted.

c. abundances of chemical species in a circumstellar shell, by solving a chemical-reaction network.

The purpose of the predictive models (item iii above) is to understand and identify the dominant physical/chemical processes at work in a given environment. The confrontation of these simulations with the derived stellar parameters and abundances constraints the input physics/chemistry.

In the following, we provide details about some of the above-mentioned tools, which are specific to our team.

MARCS

Supplementing previous releases of MARCS models (Gustafsson et al 2008), our team has calculated a grid of about 2500 models with peculiar surface abundances typical of the S-type spectra (enhanced in carbon and s-process elements; Van Eck et al. 2001). Such models will be essential for WP1.

STAREVOL

The *STAREVOL* code is a recognized key player in the stellar-evolution community for its contributions in the domains of pre-main sequence evolution (Siess et al. 2000), rotational mixing (Palacios et al. 2006), super-AGB evolution (Siess 2006), asymptotic giant branch stars (Siess et al. 2002) and associated s-process nucleosynthesis. In parallel, nuclear databases (NACRE I & II, Bruslib) are developed and maintained at ULB along with the codes able to follow the s-process nucleosynthesis (Goriely & Siess 2001). This code will be used in WP1.

BINSTAR

The state of the art in binary modelling consists of two approaches. On one hand, synthetic binary models (e.g. Hurley et al. 2002) merge the results of detailed single-star modeling, but fitted to formulae or tabulated for fast evaluation, with binary-evolution algorithms. While these are excellent tools to explore the binary-star parameter space in statistical studies, they still assume that each star in the binary evolves like a single star, neglecting the mixing of chemicals and angular-momentum transport. On the other hand, binary stellar evolution codes have been developed to follow in detail the evolution of each component of the system. So far, most of these simulations considered massive stars and focused on mass transfer prior to the supernova explosion, on the formation of gamma-ray bursts or on the neutron star spin rates (e.g. Yoon and Langer 2005). Over the past years, a considerable effort has been dedicated to the development of a new binary stellar evolution code named BINSTAR (Siess et al. 2013), that inherited the cutting-edge description of stellar physics from STAREVOL. But simulating a binary system is more complicated than just solving for two stars separately because stars interact. BINSTAR includes prescriptions describing mass transfer via winds (Hoyle & Lyttleton 1939), Roche lobe overflow (Kolb & Ritter 1990), tidal interactions (Zahn 1989) and is also capable of calculating in a fully consistent way the evolution of the orbital eccentricity (Siess et al 2014, Merle et al. 2014). Such a comprehensive modeling of binary evolution including the above effects has never been attempted before and will be explored in WP2.

RADMC-3D

This 3D Monte-Carlo radiative-transfer code (Dullemond 2012) is specifically designed to handle radiative transfer in dusty circumstellar media under various geometries.

MoD (More of DUSTY)

DUSTY is a publicly available dust radiative-transfer code (Ivezic et al. 1999). MoD is an extension of that (available upon request) that allows for more complicated density structures (Groenewegen 2012). More importantly, DUSTY was included as a subroutine in a minimization code to allow a direct comparison with photometric, spectroscopic and visibility data and find the best-fitting values of luminosity, dust optical depth, and inner dust radius.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

WP1 (“Diagnostics of nucleosynthesis and mixing in stars”)

The goals of WP1 are to identify the necessary conditions for the occurrence of the dredge-ups and mixing processes needed to produce s-process elements and to bring them to the surface:

> **Goal i.** Identify the necessary conditions for the occurrence of the third dredge-ups (TDU) and mixing processes needed to produce s-process elements and to bring them to the surface.

The Hertzsprung-Russell diagram (HRD) for a sample of S (intrinsic and extrinsic) stars with reasonably small errors on the Gaia parallax (i.e., parallax / parallax_error > 3) has been constructed [Papers 10 & 37], as will be described under WP2 below. This allowed us to locate intrinsic and extrinsic S stars relative to the locus of first occurrence of TDUs (Figure 2). **Intrinsic and extrinsic S stars segregate as expected, with intrinsic S stars falling above that locus, and extrinsic stars below it** (with the exception however of one extrinsic S star - The reason for that discrepancy could not be identified so far).

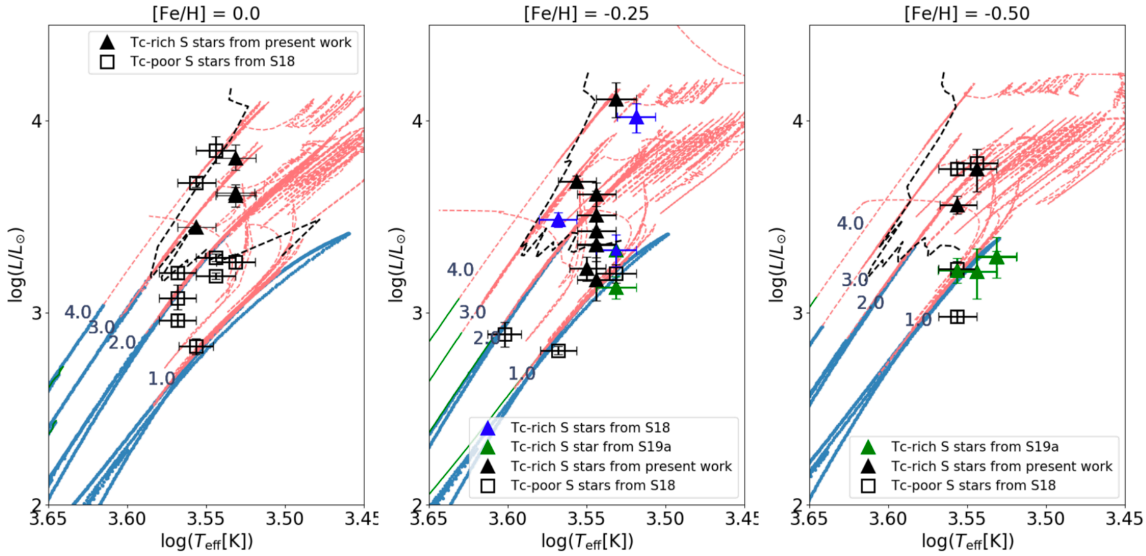

Figure 2 [From Paper 35]. HRD of intrinsic (filled triangles) S stars from Papers [10,21], as well as of extrinsic (open squares) S stars from Paper [10] along with the STAREVOL evolutionary tracks corresponding to the closest metallicity grid point. The red giant branch is represented with blue dots, the core He-burning phase with green solid lines, whereas the red dashed lines correspond to the AGB tracks. The black dotted line represents the predicted onset of TDU corresponding to the lowest stellar luminosity following the first occurrence of a TDU episode (when the convective envelope penetrates in the intershell zone where the thermal pulse was located).

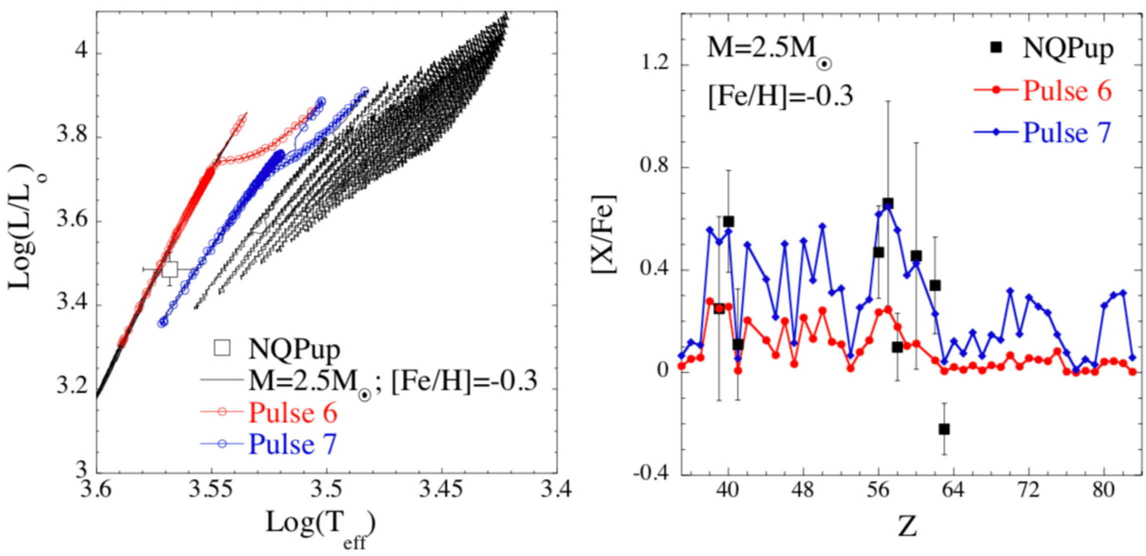

Figure 3 (From [10]). *Left panel*: Location of the intrinsic S star NQ Pup in the HR diagram, compared with STAREVOL tracks of the corresponding metallicity. *Right panel*: predicted abundance distribution from the corresponding STAREVOL models.

Quite interestingly, **the location of some of the intrinsic S stars in the HRD implies a mass on the order of 1 Msun** [Paper 21 and green triangles on Figure 2], contrary to former theoretical predictions which set 1.5 Msun as the threshold below which S stars were not predicted to occur. The existence of intrinsic S stars with masses as low as 1 Msun could be accounted for by fine-tuning the parameters describing the mixing process responsible for the operation of the neutron source triggering the s-process of nucleosynthesis, as described in Paper [21]. This narrowing of the parameter space is an important result whose consequences on higher-mass stars would need to be investigated. There is a reasonable agreement between the measured and predicted s-process abundance profiles. For 2 objects however (CD -29°5912 and BD +34°1698), the predicted C/O ratio and s-process enhancements do not match simultaneously the measured ones.

The work described in Paper [21] has been the topic of the 19/06/2019 issue of Daily Science (see Section 5.1 below).

For all S stars studied in papers [10,21,36,37], the heavy-element abundances were compared to nucleosynthesis predictions from our STAREVOL code, and this comparison allowed us to identify the pulse number, stellar mass and metallicity able to fit the observed abundances (Figure 3). This comparison is quite satisfactory in the sense that the matching model corresponds to a stellar mass and luminosity (i.e., pulse number) consistent with the star location in the HRD, an agreement which was not guaranteed *a priori.*

Goal ii. Characterize the properties of the s-process nucleosynthesis (efficiency and temperature) as a function of metallicity. This may be done using specific unstable nuclei (like Tc and ^{93}Zr) or their beta-decay product like Nb (Neyskens et al. 2011, Neyskens 2013), and hs/ls or vhs/ls ratios (where vhs denotes any element belonging to the third s-process abundance peak – like Pb – , hs denotes any element belonging to the second peak – like Ba – , and ls denotes any element belonging to the first peak – like Sr –).

To set the stage, we briefly recall the definition of extrinsic and intrinsic stars, for the specific case of S stars. S stars come in two flavours, intrinsic and extrinsic (actually, our work identified as well the new class of "trinsic" stars that we describe below [34]). Intrinsic S stars produce their s-process elements through currently on-going internal nucleosynthesis, whereas extrinsic S stars have been polluted, in the past, by an AGB companion that has since evolved into a white dwarf (WD). This scenario is supported by the following observational facts. Intrinsic S stars are defined as Tc-enriched S stars. Technetium (Tc) is an s-process element with no stable isotope. The detection of Tc in intrinsic S stars indicates that they are AGB stars that are producing s-process elements, including Tc, currently in their own interior. They undergo third dredge-up (TDU) episodes to transport the s-process elements to their surfaces, where they are detectable. On the other hand, extrinsic S stars are defined as the technetium-poor ones. The isotope ^{99}Tc (with a half-life $\tau_{1/2}$ of 210 000 yr), synthesized by the s-process, had time to decay since its production in the companion star and the mass-transfer event. The extrinsic S stars are not yet evolved enough on the AGB to produce s-process elements themselves or to undergo a TDU [10], as we showed above, under 'Goal i'. They have been shown to be all binaries (see [Paper 20] in relation with WP2).

Another radio-isotope corroborates this scenario: intrinsic S stars are not enriched in Nb (since mono-isotopic ^{93}Nb has not yet been produced by the ^{93}Zr decay with $\tau_{1/2}$ = 1.6 10^6 yr) while extrinsic S stars are niobium-rich (Figure 4).

Figure 4 (from Papers [10,36]) very clearly shows this intrinsic / extrinsic dichotomy as revealed by the [Nb/Zr] ratio: the extrinsic S and barium stars are Nb-rich and fall along the diagonal, whereas the Zr-rich, Nb-poor intrinsic S stars fall above the diagonal.

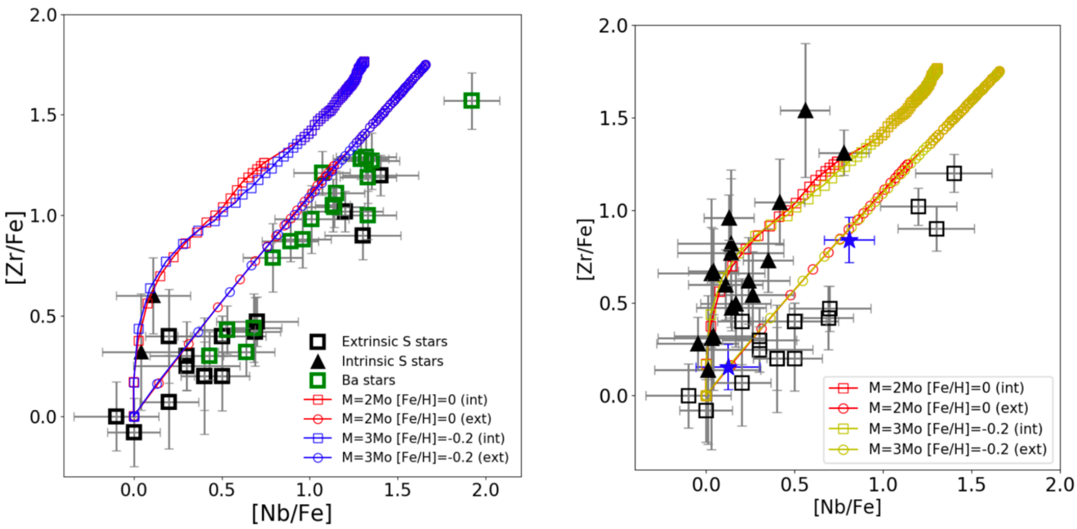

Figure 4 (From [10] left panel and [37] right panel): The ([Zr/Fe], [Nb/Fe]) plane. Different kinds of stars are represented by different symbols as labelled in the lower right corner. The red and blue lines in the left panel represent the surface abundance predictions from the models. Each thermal pulse is indicated by a symbol: circles correspond to surface abundances of extrinsic stars, i.e. after the full decay of ^{93}Zr into Nb, and squares to intrinsic S stars still on the AGB. On the right panel, the blue star symbols correspond to the new class of 'trinsic' stars, i.e., binary AGB stars with a large Nb abundance.

A **new category of "trinsic" S stars** is revealed by the right panel in Figure 4 (blue star symbols) : they show signatures of both intrinsic and extrinsic S stars, since they are Tc-rich like intrinsic S stars are, but nevertheless fall along the diagonal in the (Zr - Nb) plane, as extrinsic S stars do. They are actually binary S stars (thus extrinsic, as shown by WP2 [Paper 20]) which evolved far enough along the AGB to start the intrinsic s-process nucleosynthesis (thus they are Tc-rich), as revealed by [36].

Finally, a **detailed abundance study of the Carbon-Enriched Metal-Poor (CEMP) stars** [34] revealed the existence of some extrinsic stars (like HD 209621 displayed on Figure 5) that were polluted by matter irradiated with neutron densities much larger (~10^{15} neutrons/cm^3) than typically expected for the s-process of nucleosynthesis (~10^8 neutrons/cm^3), more typical of the i-process (for "intermediate" between the s- and the r-processes). While the s- and r-processes[1] are rather well understood separately, the origin

[1] As a reminder, the s-process produces through successive neutron captures elements heavier than iron within the valley of β stability, whereas the r-process requires large neutron

of the peculiar abundance pattern in the so-called r/s-stars showing enhancements of both s-process and r-process elements is still an open question (Barbuy et al. 1997; Hill et al. 2000; Gull et al. 2018, and references therein). The i-process can be induced in the STAREVOL models by modifying the mixing parameters, so as to force the proton ingestion directly within the thermal pulse, thus triggering a large neutron density. The agreement between observed and predicted abundances as displayed in Figure 5 is important as it reveals that the operation of the i-process does not necessarily require very exotic conditions, as is sometimes advocated in the literature.

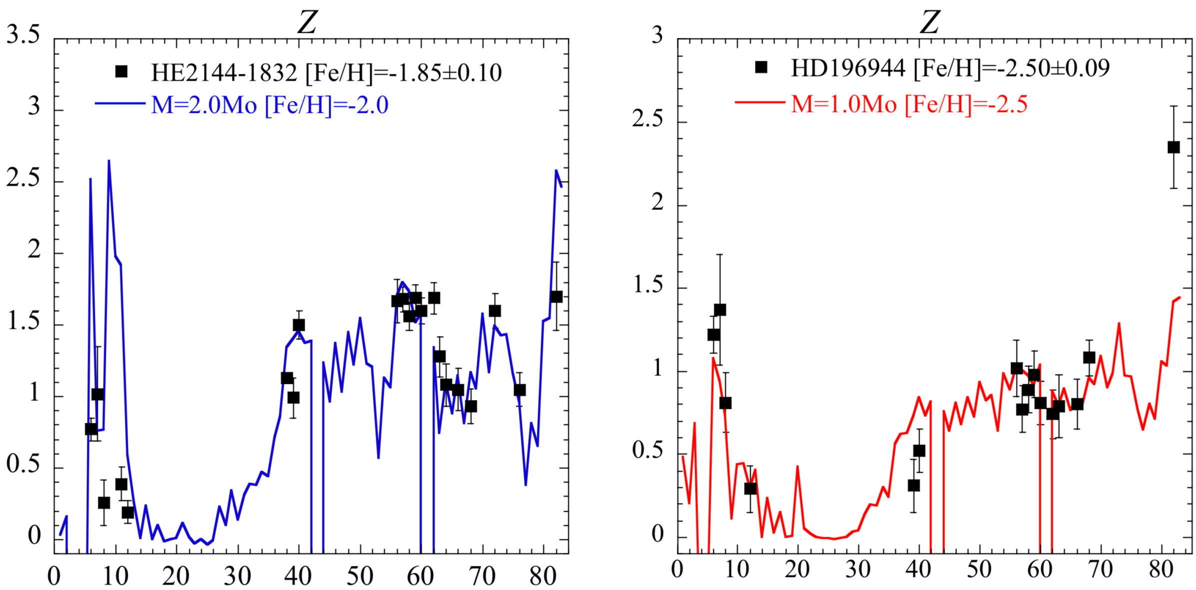

Figure 5 (From [34]). Observed abundance pattern (black squares) in the CEMP stars HE2144-1832 (left panel) and HD 196944 (right panel) of metallicities [Fe/H] = -2.0 and -2.5, respectively. The red and blue curves correspond to STAREVOL predictions for the i- and s-processes, respectively. Note the discriminating power of the elemental abundances in the *Z* range 55 - 70.

Goal iii. Clarify the evolutionary link between AGBs and post-AGBs, by comparing all available observational constraints (abundances, orbital elements, luminosities).

This topic has not been fully explored. A restricted discussion of that issue is going to be presented in Paper [37] based on a comparison of abundances in S and post-AGB stars, whereas a comparison of their orbital elements is presented in Figure 9 below (panels e and h, based on Papers [5,11,22], and published in Paper [31]), in the framework of WP2. The conclusion that emerges from this comparison is that the link between AGB and post-AGB stars is not as straightforward as their related names would seem to suggest, since both abundances and orbital elements show striking differences. This issue will require further investigation in future studies.

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densities to synthesise neutron-rich nuclei located on the neutron-rich side of the valley of β stability.

WP2 (”Uncovering the link between the various classes of binaries involving evolved low- and intermediate-mass stars”) :

> **Goal i.** Identify the binary-evolution channel leading to specific families of LIMS binaries like dusty-disc post-AGB systems, dwarf Ba stars and giant Ba stars.
>
> **Goal ii.** as a corollary to Goal i, understand how these various families are linked to each other.

To identify and account for the links between the various classes of binary systems involving stars chemically-polluted by their companion (the so-called *extrinsic* systems; see WP1), we started by comparing the location of several families of extrinsic stars (namely extrinsic S stars, barium dwarfs and giants, and CH subgiants) in the Hertzsprung-Russell diagram (HRD), using the recently released Gaia data. The next step is to compare these respective locations in the HRD with the orbital parameters, to possibly find evolutionary signatures imprinted on the orbital parameters (like for instance an orbital period threshold imprinted by the large radius reached at the tip of the red giant branch).

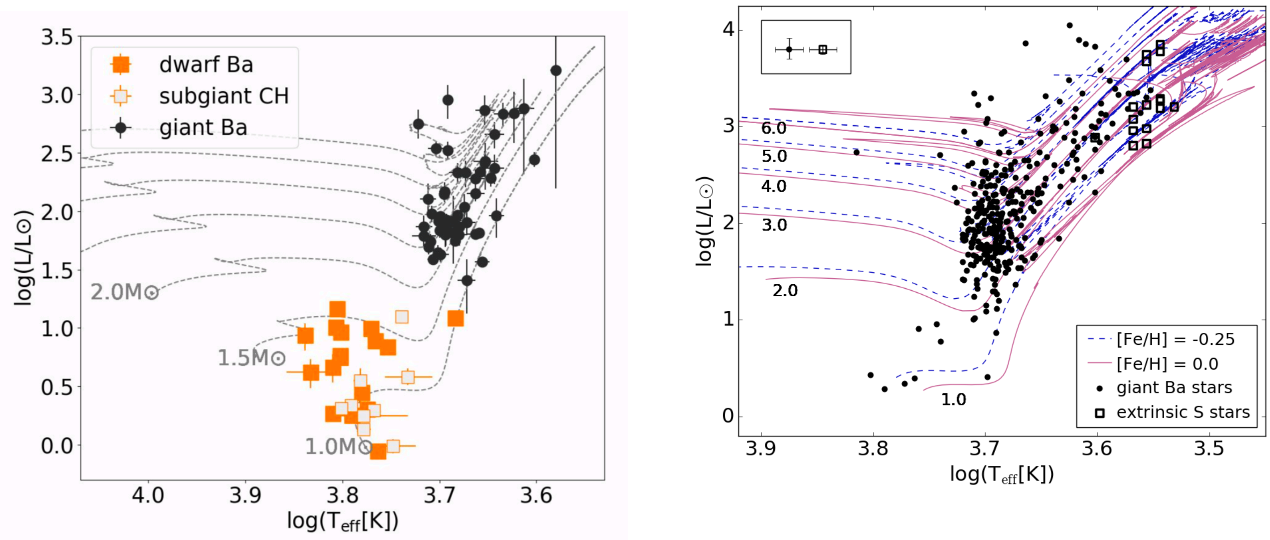

Figure 6 (From [10] for the right panel and [32] for the left panel). Left panel: HRD of dwarf and giant barium stars, as well as subgiant CH stars. STAREVOL evolutionary tracks with metallicity [Fe/H] = −0.25 are overplotted. Right panel: Same as left panel for extrinsic S stars and giant barium stars.

Figure 6 presents the HRD of giant Ba, dwarf Ba, subgiant CH stars and extrinsic S stars, constructed from the Gaia second data release [4,10,32]. It appears from this figure that (i) subgiant CH stars are undistinguishable from dwarf Ba stars, and need not be classified as a distinct class; (ii) extrinsic S stars are the cooler analogues of the low-mass barium giants; (iii) dwarf barium stars (seem to) cover a more restricted mass range than giant barium stars, but this is the result of an observational selection bias against more massive barium dwarfs. Mass distributions could be derived for all these classes (Figure 7) from their location in the HRD compared to evolutionary tracks from the STAREVOL code. Combined with the orbital elements (more specifically the so-called "mass functions") and with the assumption of random orientation of the orbital planes, the knowledge of the primary masses enabled us to derive the mass of the companion, most likely a white dwarf (WD), the progeny of the former AGB polluter. This hypothesis turned out to be valid, since the companion's mass distribution is peaked at 0.5 - 0.6 Msun while covering the range 0.5 -1.1 Msun, as expected for WDs (Figure 8; [19,20]), although the distribution of field WD masses is narrower than that of WDs around barium stars.

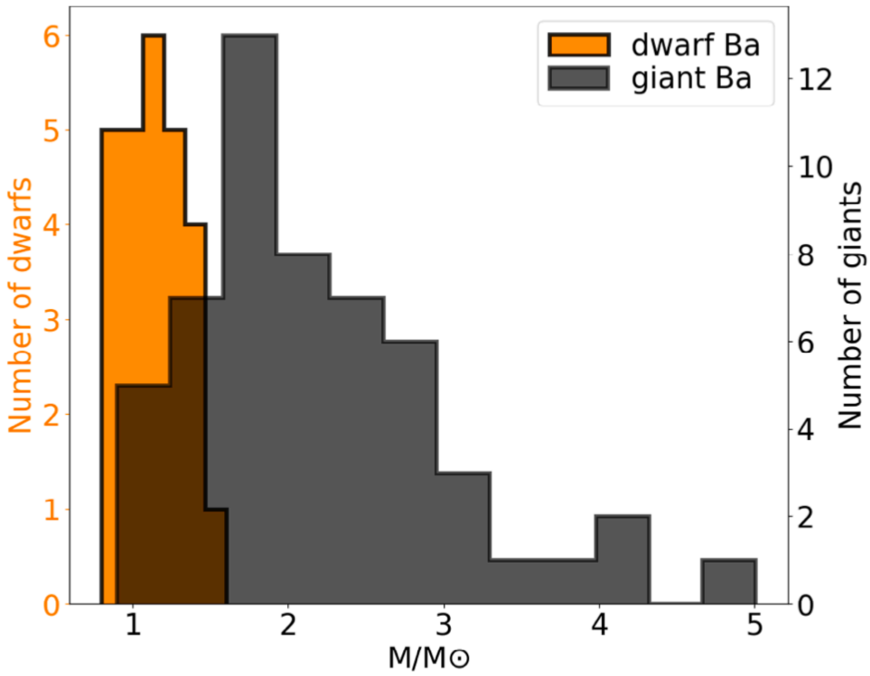

Figure 7 (From [32]). Mass distribution for dwarf and giant barium stars.

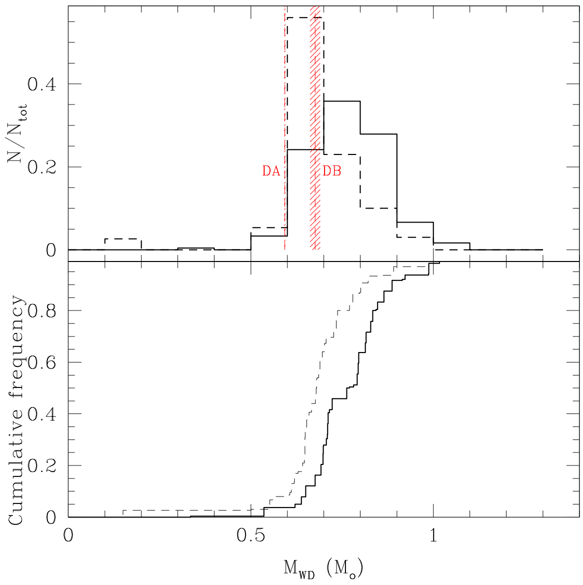

Figure 8 (From [20]): Top panel: Mass distributions of WDs orbiting mild and strong barium stars (dashed and solid lines, respectively). The red shaded areas labelled DA and DB correspond to the average masses for field WDs. Bottom panel: Cumulative mass distributions corresponding to the two samples from the top panel.

Similarly, the HRD of binary RV Tau stars (i.e., luminous Cepheid pulsators with alternating deep and shallow minima) from the solar neighbourhood has been drawn (Figure 9, from Paper [5]). It reveals the presence of some post-RGB stars (those below the red line in Figure 9), instead of post-AGB stars as expected. Post-RGB stars are the results of strong binary interaction on the Red Giant branch (RGB) rather than on the AGB, and responsible for the loss of their envelope, making them evolve to the left (i.e., towards higher temperatures) in the HRD. Thus, as already found by Kamath et al. (2015) for "post-AGB" systems from the Large Magellanic Cloud (LMC), RV Tau systems should as well be considered as a mixture of post-RGB and post-AGB stars. And obviously the same conclusion holds true for the sample of RV Tau stars in the LMC and SMC (Figure 10, from Paper [16]), which contains a few RGB stars as well.

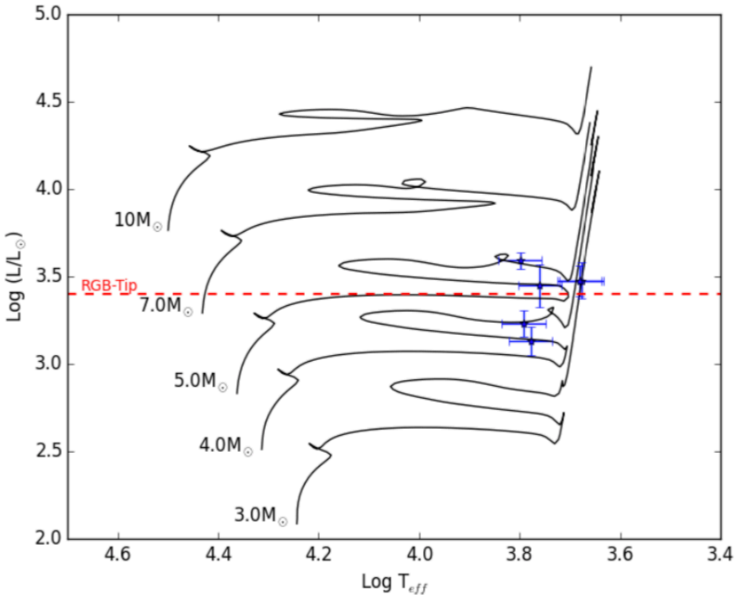

Figure 9 (From [5]). Position of the Galactic RV Tauri stars on the HRD. The dark lines are evolutionary tracks from Bertelli et al. (2009). The red dashed line shows the RGB-tip at 2500 L_{sun}. The positions of TW Cam and IRAS 17038-4815 nearly coincide.

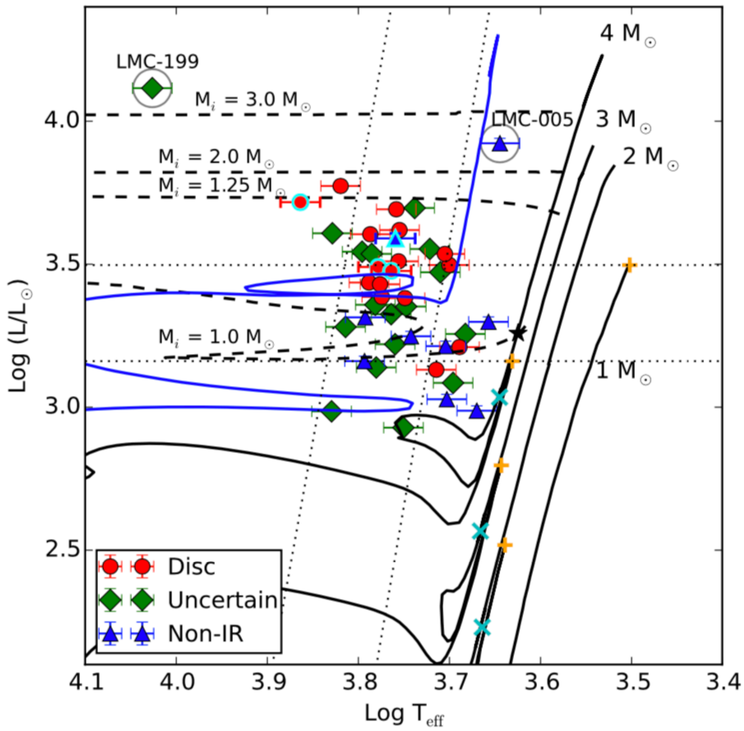

Figure 10 (from [16]): LMC RV Tauri stars with different spectral-energy distribution (SED) characteristic (i.e., disc-like, no IR excess, uncertain), plotted in the HRD. The black lines are evolutionary tracks for 1 M_{sun}, 2 M_{sun}, 3 M_{sun}, and 4 M_{sun} stars with composition Z = 0.008 and Y = 0.26 for the LMC (Bertelli et al. 2009). The dashed lines are post-AGB tracks from Miller Bertolami (2016) for 1 M_{sun}, 1.25 M_{sun}, 2 M_{sun}, and 3 M_{sun} initial-mass stars with an initial metallicity Z = 0.001. The blue line represents the evolution of a 3 M_{sun} star, which goes through a blue-loop phase.

The slanted dotted lines show the theoretical Cepheid instability strip taken from Kiss et al. (2007). The tips of the RGB for each track corresponding to the mean metallicity of the LMC are indicated with orange '+' signs, at L ≥ 3150, 330, 630, and 1450 L_{sun} for the 1, 2, 3, and 4 M_{sun} tracks, respectively. The upper and lower horizontal dotted lines indicate the tip of the RGB for 1 and 4 M_{sun} stars, respectively. The cyan 'x' markers represent the start of the early AGB phase (E-AGB); these markers are at L = 170, 370 and 1090 L_{sun} for the 2, 3 and 4 M_{sun} tracks, respectively.

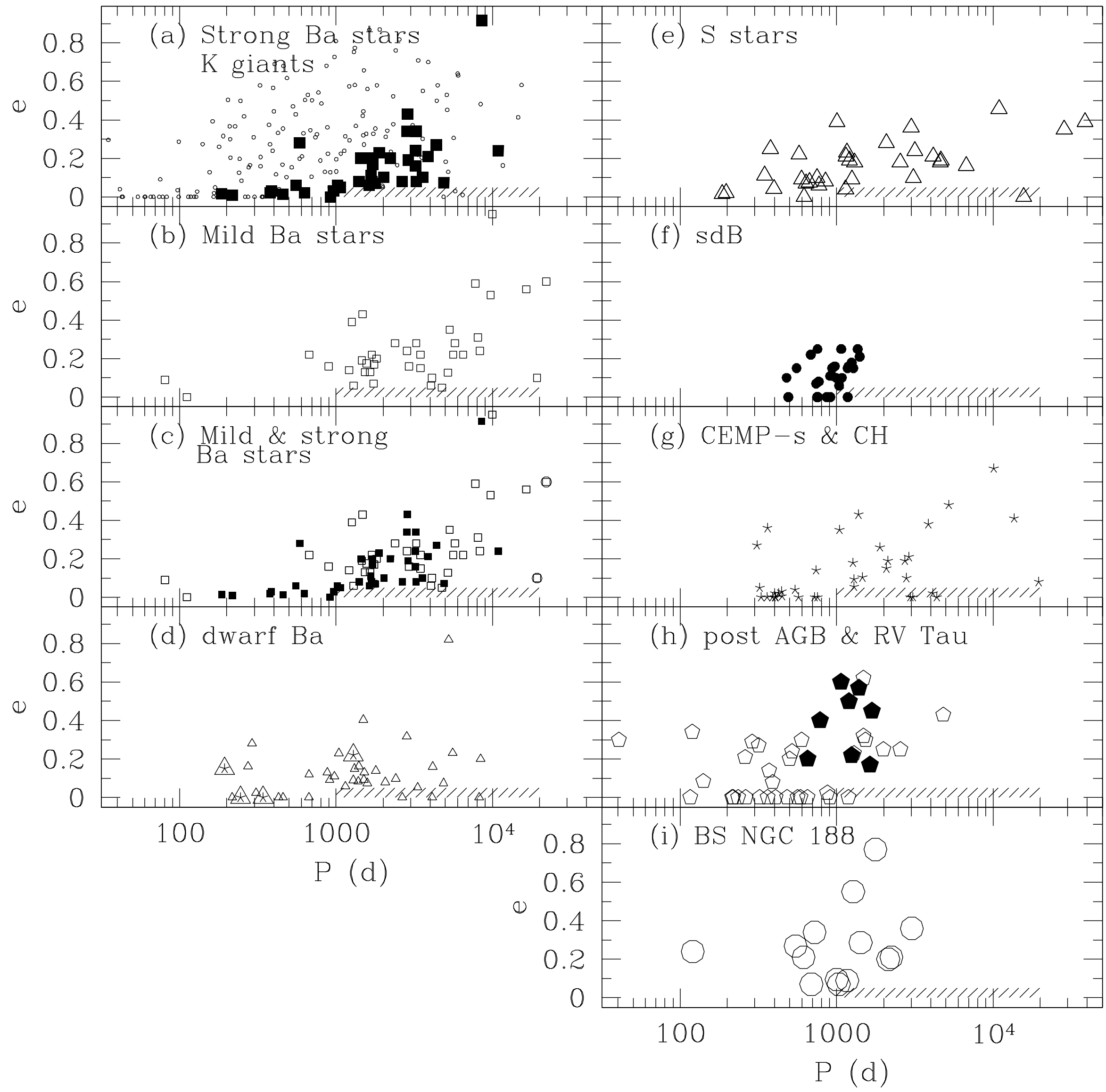

Fig. 11 (From **[31]**): A compendium of eccentricity -- period diagrams for post-mass-transfer binaries: **(a) Strong barium stars** (large filled squares; with orbital data **[18]**), along with the comparison sample of (mostly) pre-mass-transfer binaries (**G and K giants in open clusters** from Mermilliod et al. 2007; small open circles). The lower-right hatched area corresponds to an avoidance zone; **(b) Mild barium stars**, small open squares, with data as for (a); **(c) Strong and mild barium stars** altogether; **(d) dwarf and subgiant barium and CH stars**, with data from McClure et al. (1997) and **[17]** (open triangles), and a few dwarf CEMP-s stars (crossed open triangles). Systems falling in the avoidance region likely have inaccurate orbits. Some dwarf CEMP-s and carbon stars, not

represented on the figure, may have orbital periods as short as a few days; **(e) extrinsic S stars** (open triangles), with data as for (a); **(f) sdB binaries** (filled circles), with data from Deca et al. (2012), Vos et al. (2012), Barlow et al. (2012), and Vos et al. (2019); **(g) CH, CH-like, and CEMP-s stars** (crosses), with data from **[3]**; **(h) post-AGB** (open pentagons) and **RV Tau** (filled pentagons) stars, with data from **[5,11]**; **(i) NGC 188 blue stragglers** (large open circles), with data from Gosnell et al. (2015). The avoidance region in the eccentricity – period diagram ($P > 10^3$ d, $e < 0.07$, represented by the hatched area) is clearly present in all families.

An important diagnostic of binary evolution resides in the eccentricity - period (e - P) diagram. Figure 11 is one of the major outcomes of STARLAB WP2 since it results from the collaborative effort invested by the STARLAB consortium members in securing radial velocities for various binary families with the HERMES spectrograph over a 10-yr time span (combined in some cases with 25-yr older CORAVEL data). As indicated in the caption of Figure 11, the data to build this e - P diagram were obtained from many papers produced in the STARLAB framework. Moreover, the comparison of Figure 1 with panels c and e of Figure 11 allows the reader to evaluate at a glance the progress achieved thanks to the STARLAB project, especially in the better definition of the upper eccentricity envelope and in finding the longest orbital periods. Actually, for barium and extrinsic S stars, all orbits have now been obtained in our samples, meaning that the maximum orbital periods that may be found in these post-mass-transfer systems is about 4×10^4 d, or about 100 yr.

From the e - P diagrams of Figure 11, several important results may thus be inferred:

(i) The upper-period threshold for efficient s-process pollution has been found to be about 100 yr, an important constraint for future hydrodynamic simulations of mass transfer;

(ii) Barium dwarfs and giants are found to occupy the same region of the e - P diagram, with the exception of somewhat eccentric dwarf-barium binaries at short periods. Almost all barium systems with periods shorter than 10^3 d are circular, and this property is likely attributable to the circularisation occurring as the barium-dwarf systems ascend the red giant branch (RGB), as demonstrated by our binary stellar-evolution models computed with the BINSTAR code [36]. Since extrinsic S systems are still ascending the RGB, not all are circularised yet, contrarily to barium giants since most of them reside in the red clump, thus posterior to the RGB evolution. The circular or eccentric nature of the short-period systems is the only dynamical property that distinguishes extrinsic S systems from barium systems;

(iii) Eccentric, short-period systems are even more numerous among post-AGB systems [11] than among dwarf barium stars. If barium dwarfs are indeed the progenies of post-AGB binaries, this discrepancy suggests that an additional circularisation process must operate between the post-AGB stage and the dwarf barium stage;

(iv) The relationship between binary RV Tau stars and post-AGB systems has been investigated as well [5,11,22]: despite the similarity of their evolutionary status (when excluding the post-RGB systems described above), RV Tau systems have on average much longer orbital periods (> 700 d) than post-AGB systems (> 100 d), but the reason thereof has not been identified so far. Otherwise, RV Tau and post-AGB stars behave similarly in terms of the presence of an infrared excess starting at about 10 μm in the binary systems, and attributable to a Keplerian circumbinary disc where hot dust is stored [5,15,22];

(v) Finally, not plotted on Figure 11, the family of binary central stars of planetary nebulae (CSPN) has been extended to include several new members thanks to HERMES and SALT (South African Large Telescope) observations [6,12,13,23], comprising several new cases with long periods. The latter cases reinforce the link between CSPN, post-AGB systems and barium systems. On the other hand, the discovery of several CSPN with short orbital periods strengthen the case that a large fraction of planetary nebulae may be remnants of common-envelope binary evolution, rather than the photo-ionized remnant of normal (single-star) AGB evolution, after envelope ejection, as was thought so far;

(vi) The systems collected in Figure 11 represent a sample of about 200 post-mass-transfer systems with known orbital elements which will serve in the future as test bench for binary-evolution models.

Goal iii. Confront the abundance pattern at the surface of these LIMS binaries with predicted abundances.

Most of this objective was handled by WP1 (Figures 3-5). Nevertheless, in the context of WP2, chemical properties of post-mass-transfer systems have been compared with orbital elements, in order to reveal possible correlations between them. A weak correlation has been found between orbital period *P* and the yttrium overabundance [Y/Fe] (Figure 12, from Paper [20]), suggesting that there must be several other intervening parameters, the most important one being the initial mass ratio *q* of the binary system (the correlation coefficient linking [Y/Fe] and *P* and is 0.462; the correlation coefficient linking [Ce/Fe] and *q* is 0.489). Indeed, the mass ratio controls both the efficiency with which s-process elements are being produced by the AGB progenitor (massive AGB progenitors are expected to be weak heavy-elements producers) and the factor with which they are diluted in the accreting star (the more massive this star, the stronger the accreted matter will be diluted).

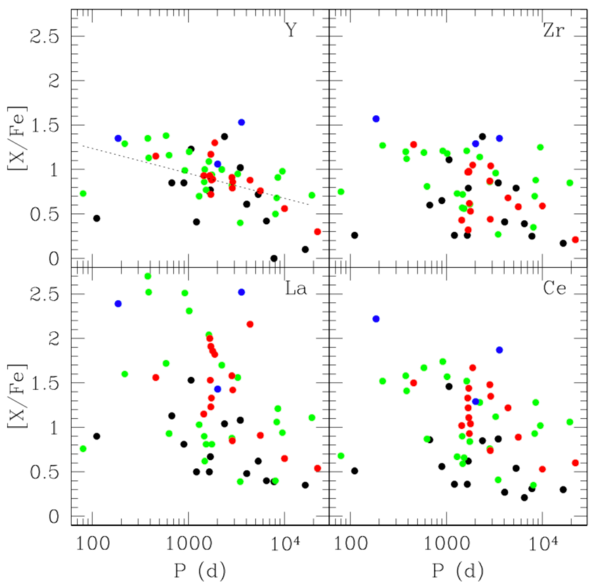

Figure 12 (From Paper [20]). Period–abundances relationship for s-process elements Y, Zr, La, and Ce. In the panel corresponding to Y, the dotted line is a least-square fit to the data, illustrating the trend existing with orbital period. Blue ([Fe/H] < −0.6), red (from −0.6 to −0.3), green (from −0.3 to −0.1), and black ([Fe/H] ≥ −0.1) symbols denote stars of increasing metallicities.

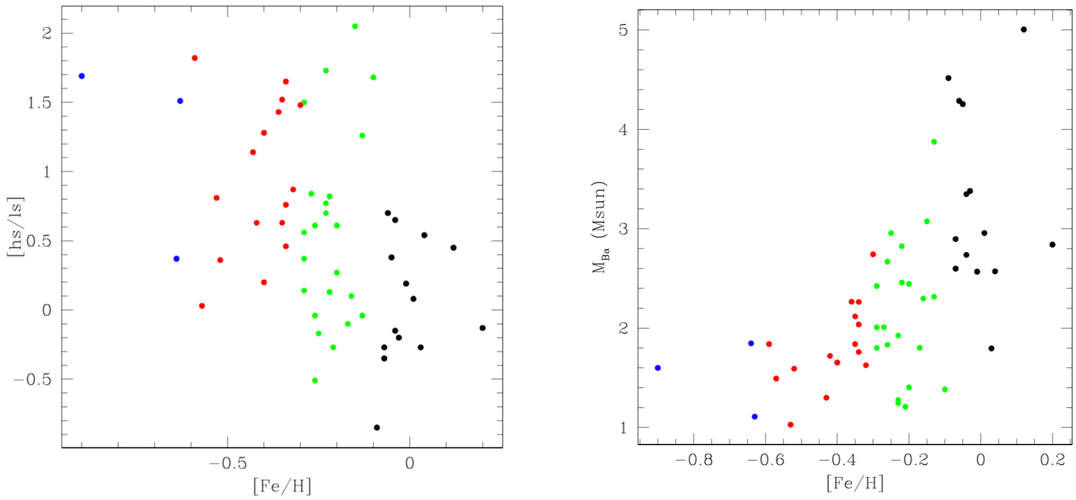

Figure 13 (From Paper [20]). Left panel: Efficiency of the s-process expressed as [hs/ls] ≡ ([La/Fe] + [Ce/Fe]) − ([Y/Fe] + [Zr/Fe]) as a function of metallicity [Fe/H] and color-coded as in Fig. 12. Right panel: Barium-star mass vs. [Fe/H], color-coded as the left panel.

Other findings from our abundance analysis of barium stars is the confirmation of the long-standing [hs/ls] - [Fe/H] relationship (Left panel of Figure 13) and the strong mass - metallicity relation for barium stars (Right panel of Figure 13), probably a straightforward consequence of the chemical evolution of our Galaxy.

WP3 ("Circumstellar matter on different spatial scales: Signatures of mass-loss processes and signatures of binary interaction") :

Goal i. Achieve an in-depth understanding of the effects shaping the outflows around evolved stars, by studying the morphology on the smallest spatial scales through analysis of mid-IR interferometric data.

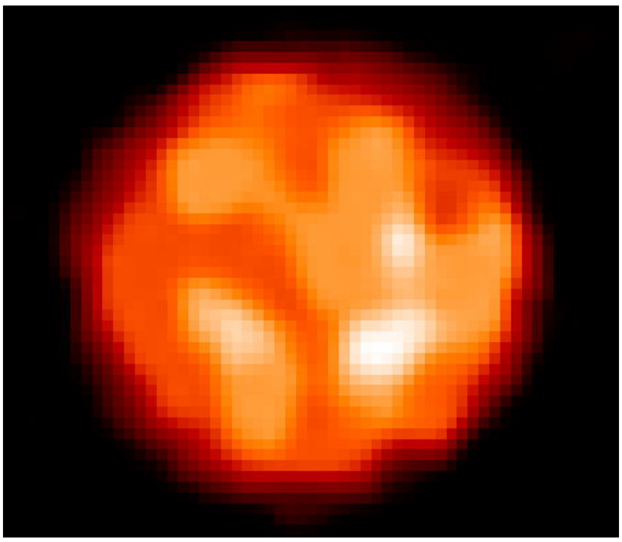

Figure 14 (From Paper [8]). The surface of the S star π^1 Gruis, imaged from PIONIER interferometric data in the H band. © Nature

A first result towards this goal was obtained using VLTI/PIONIER data to image the surface of the S-type star π^1 Gru [Paper 8 and ESO/ULB press release in Sect. 5.1]. It shows a few large convective cells (Figure 14), whose size was compared to the predictions of three-dimensional models of convection. A quite satisfactory match was obtained. Future studies will need to evaluate the evolutionary timescale of these surface structures.

A second result pertaining to this goal is presented in Paper [35], which addresses the following questions: is it possible to identify features in dusty spectral energy distributions (SEDs) that are caused by specific dust-cloud morphologies? Are these signatures unique to specific morphologies? We also investigated the possibility of the opposite case where different morphologies with different dust masses possibly give rise to the same SED. With this, we want to evaluate by how much CSE dust masses may be mis-estimated when adopting an incorrect dust morphology. It was decided to use EP Aqr as benchmark star for this study, because this star most likely belongs to a binary system, as revealed by the spiral structure characterizing its circumstellar (CS) dust shell. The system has been used as a benchmark to evaluate the impact of the CS geometry on the SED, and in particular, whether dusty spirals (associated with binary systems) leave a specific signature in the SED that would permit to distinguish them from spherical CS. The parameter space has been explored in this respect using the RADMC-3D code, by evaluating the impact on the mass-loss rate, not only of the geometry (spiral vs spherical with the same dust mass), but also of scattering, and of the inclination of the spiral plane with respect to the plane of the sky. The most important results are presented in Figure 15, revealing that the SED alone cannot be used to discriminate between different CS geometries. Best-fitting SEDs with different geometries have dust masses ranging from $5\ 10^{-7}$ to $1.5\ 10^{-5}$ Msun. We conclude that the knowledge of the CS geometry is necessary to obtain accurate CS dust masses and consequently, accurate mass-loss rates.

Goal ii. Study the overall mass-loss process, dust composition and structure of the CSE from analysis of Herschel PACS and SPIRE spectra. This is obviously connected to the first aim, but uses data at longer wavelengths, and at larger, even global, spatial scales.

To this aim, we analysed in Paper [9] Herschel PACS (55 µm – 190 µm) and SPIRE (200 µm – 680 µm) high-resolution spectra for 27 M stars (23 asymptotic giant branch including a few OH/IR stars, and 3 red supergiant stars), 3 S-type stars, and 10 C-type stars. They span a mass-loss range from 10^{-4} to 10^{-9} Msun yr $^{-1}$. Paper [9] presents the library of Herschel PACS and SPIRE data containing measured (and identified) molecular lines, and quality-checked dust continua for the above-mentioned sample of stars. The following data products are released: the reduced spectra, the lines that are measured in the spectra with wavelength, intensity, potential identifications, and the continuum spectra, i.e. the full spectra with all identified lines removed. As simple examples of how these data can be used in future studies, we have fitted the continuum spectra with three power laws (two wavelength regimes covering PACS, and one covering SPIRE) and find that the few OH/IR stars seem to have significantly steeper slopes than the other oxygen- and carbon-rich objects in the sample, possibly related to a recent increase in mass-loss rate. This confirms the existing ideas that these sources are suffering from very recent, heavy mass loss. As another example, we constructed rotational diagrams for CO (and HCN for the carbon stars) and fitted a two-component model to derive rotational temperatures, that may be used to characterize the temperature of the circumstellar shell.

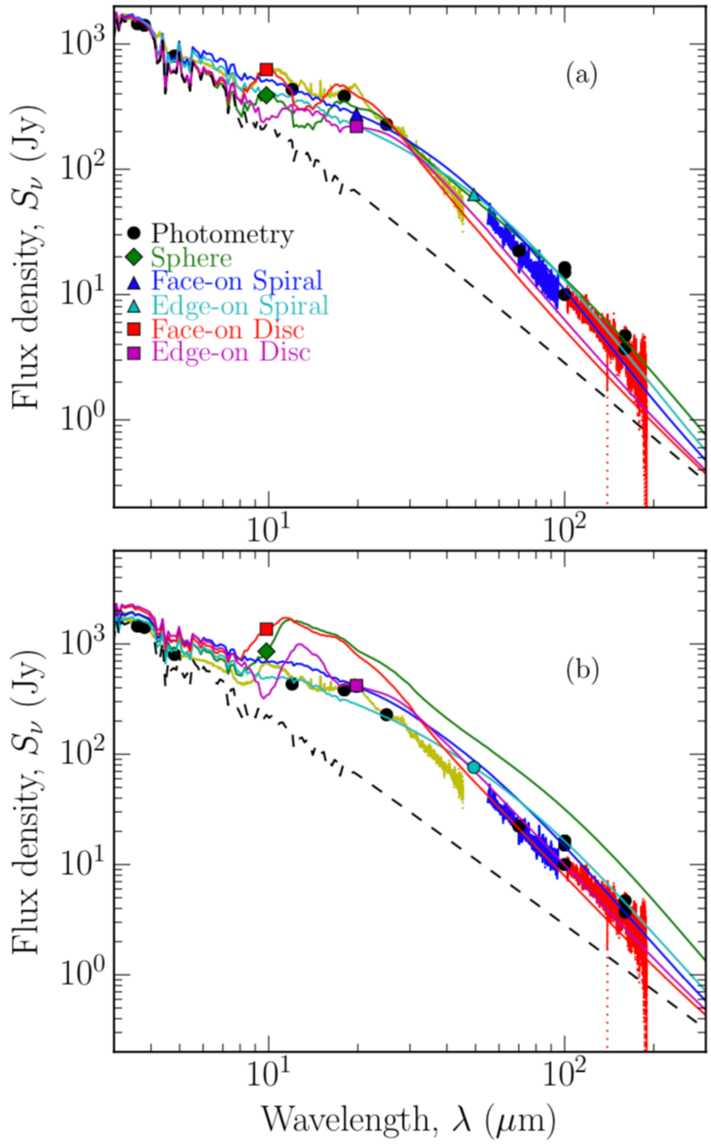

Figure 15 (From Paper [35]): Comparison between best-fit models, photometry and IR spectra for EP Aqr. The top panel (a) uses dust with 99% Mg_2SiO_4 and 1% Fe_2SiO_4. The bottom panel compares the same dust masses and morphologies with these dust species: 90% Mg_2SiO_4, 9% Al_2O_3, and 1% Fe_2SiO_4. The spherical dust SED is displayed in green (diamonds), the spirals are in blue (face-on) and cyan (edge-on) with triangles, the discs are red (face-on) and magenta (edge-on) with squares. The black dashed curve is the stellar photosphere SED model. The yellow spectrum is from ISO/SWS (Sloan et al. 2003). The blue and red spectra are from *Herschel*/PACS (Paper [9]). The observed photometry is shown as black dots (the error bars were smaller than the symbols and not are shown here).

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5. DISSEMINATION AND VALORISATION

5.1 Highlights

Ph.D. theses. Three Ph.D. students involved in the STARLAB project have completed (or will do so in the near feature) their Ph.D. thesis: **R. Manick** (December 2018) [WP2], **S. Shetye** (September 2019) [WP1], **A. Escorza** (January 2020, now Research Assistant at FWO) [WP2]. **D. Nicolaes** [WP3] resigned in September 2017 and was replaced by the post-doc fellow **J. Wiegert.**

The STARLAB project served as a leverage to obtain post-doctoral grants for R. Manick (now at the *South African Astrophysical Observatory*) and for A. Escorza (joining the *European Southern Observatory* in the course of 2020).

Public outreach. There has been one major effort to specifically publicise the STARLAB research during one module (5 x 1h, entitled *Les étoiles en bonne compagnie : II. Evolution*) of the *Cours public d'Astronomie*, attended by about 150 people on the ULB campus in November 2018. See http://www.astro.ulb.ac.be/pmwiki/IAA/CPA#S2018 (code to download the slides: user: cepulb ; password: cpa).

A. Escorza is part of the organizing committee of the *Pint-of-science* festival (https://www.pintofscience.be/team) and the ladies@science KU Leuven festival (https://wet.kuleuven.be/ladiesatscience).

Press releases.

- On the Daily Science web site, a description of the BRAIN-Be project STARLAB has been posted, with special emphasis on Paper [21] by Shetye et al.: http://dailyscience.be/19/06/2019/avenir-fecond-pour-le-soleil/
- From ULB and ESO, about the paper *Large granulation cells on the surface of the giant star π^1 Gruis*, by C. Paladini et al., published in the journal NATURE on 21 December 2017 :

  - eso1741, https://www.eso.org/public/news/eso1741/ Giant Bubbles on Red Giant Star's Surface

  - ULB: Des cellules bouillonnantes à la surface d'une étoile géante http://www.ulb.ac.be/babelbox/ws/getfile.php5?filter=databox6-art-attach-1043.5a3b6c4d81750.pdf

5.2 Participation to conferences and seminars.

2015:

- **Stellar End Products, the Low-Mass High- Mass Connection**, European Southern Observatory workshop and seminar, Garching, Germany, 6-10 july 2015 (H. VAN WINCKEL, L. DECIN, M. GROENEWEGEN, G. VAN DE STEENE, A. JORISSEN, S. VAN ECK & C. PALADINI)

- **Gaia-ESO Survey Third Science meeting**, Vilnius, Lithuania, 1-4 December 2015 (S. VAN ECK)

- **The Physics of Evolved Stars : A conference dedicated to the memory of Olivier Chesneau**, Nice, France, 8-12 June 2015 (M. GROENEWEGEN, G. VAN DE STEENE, S. VAN ECK, H. VAN WINCKEL)

2016:

- **Binary Stars Conference**, Cambridge, UK, 25-29/7/2016. Contributed talk (available on the STARLAB/BRAIN webpage http://www.astro.ulb.ac.be/pmwiki/BRAIN/Agenda): TO BA OR NOT TO BA: THE FORMATION OF BARIUM STARS (A. ESCORZA)

- **Binary Stars Conference**, Cambridge, UK, 25-29/7/2016. Invited talk:OBSERVATIONS OF NUCLEOSYNTHESIS IN BINARY STARS (A. JORISSEN)

- **Blowing in the Wind** Conference, Quy Nhon, Vietnam, 8 August 2016. DUSTY AGB WINDS AS SEEN BY PACS & SPIRE SPECTROSCOPY (D. NICOLAES, M.A.T. GROENEWEGEN, L. DECIN)

- **Blowing in the Wind** Conference, Quy Nhon, Vietnam, 10 August 2016. Invited talk HIGH SPATIAL RESOLUTION STUDIES OF THE WINDS OF EVOLVED STARS (L. DECIN)

- **The 12th Torino workshop and 4th CSFK Astromineralogy workshop**, Budapest, Hungary, 31/7-6/8/2016. Contributed talk: PROBING AGB NUCLEOSYNTHESIS VIA DETAILED ABUNDANCE STUDIES OF S STARS (S. SHETYE)

- **The 12th Torino workshop and 4th CSFK Astromineralogy workshop**, Budapest, Hungary, 31/7-6/8/2016. Contributed talk: THE TEMPERATURE AND CHRONOLOGY OF HEAVY-ELEMENT SYNTHESIS IN LOW-MASS STARS (S. VAN ECK, A. JORISSEN, B. PLEZ, L. SIESS, S. GORIELY)

- **ICCUB School : Machine Learning and data Data Mining in Physics**, Barcelona, Spain, 17-21/10/2016 (S. SHETYE, A. ESCORZA)

- London, UK, 11 January 2016. Invited talk DYNAMICAL-RADIATIVE-CHEMICAL CODES (L. DECIN)

- Onsala, Sweden, 27 April 2016. Invited talk THE DEATH THROES OF MASSIVE STARS (L. DECIN)

- ERC-event, Leuven, 23 May 2016. Invited talk ASTROCHEMISTRY OF OLD STARS: DIRECT PROBING OF UNIQUE CHEMICAL LABORATORIES (L. DECIN)

- **COOLSTARS19 conference**, Uppsala, Sweden, 6 June 2016. Invited talk HIGH SPATIAL RESOLUTION STUDIES OF THE WINDS OF EVOLVED STARS (L. DECIN)

- **EWASS 2016 conference**, Athens, Greece, 5 July 2016. Invited talk ALMA'S VIEW ON CIRCUMSTELLAR ENVELOPES AND MASS LOSS (L. DECIN)

- Leeds, UK, 8 November 2016. Invited talk ASTROCHEMISTRY OF OLD STARS: DIRECT PROBING OF UNIQUE CHEMICAL LABORATORIES (L. DECIN)

2017:

- **IAU Symposium 330: Astrometry and Astrophysics in the Gaia sky**, 24/04/2017 – 28/04/2017 (Nice) (https://iaus330.sciencesconf.org/). Poster presentation entitled: TO BA OR NOT TO BA: THE FORMATION OF BARIUM STARS (A. ESCORZA)

- **Blaauw Symposium 2017**, 17/05/2017 (Groningen) (https://sites.google.com/view/blaauw-symposium-2017/) Oral presentation entitled: TO BA OR NOT TO BA: OBSERVATIONAL CONSTRAINTS TO THE FORMATION AND EVOLUTION OF BARIUM STARS (A. ESCORZA)

- **72nd Netherlands Astronomy Conference**, 22/05/2017 – 24/05/2017 (Nijmegen) (http://www.astronomenclub.nl/conferentie/). Oral presentation entitled: TO BA OR NOT TO BA: OBSERVATIONAL CONSTRAINTS TO THE FORMATION AND EVOLUTION OF BARIUM STARS (A. ESCORZA)

- **The impact of binaries on stellar evolution**, 03/07/2017 – 07/07/2017 (at ESO Garching) (https://www.eso.org/sci/meetings/2017/Imbase2017.html). Oral presentation entitled: TO BA OR NOT TO BA: OBSERVATIONAL CONSTRAINTS TO THE FORMATION AND EVOLUTION OF BARIUM STARS (A. ESCORZA)

- **FNRS Contact Group Astronomie & Astrophysique and Astronomy Day of the Royal Observatory of Belgium**, 18/09/2017 (Brussels) (http://www.planetarium.be/cg/index.htm). Oral presentation entitled: TO BA OR NOT TO BA: OBSERVATIONAL CONSTRAINTS TO THE FORMATION AND EVOLUTION OF BARIUM STARS (A. ESCORZA)

- **Blaauw Symposium 2017**, 17/05/2017 (Groningen) (https://sites.google.com/view/blaauw-symposium-2017/) Oral presentation entitled: DETERMINING LUMINOSITY OF THE THIRD DREDGE-UP VIA S STARS (S. SHETYE)

- **IAU Symposium 330: Astrometry and Astrophysics in the Gaia sky**, 24/04/2017 – 28/04/2017 (Nice) (https://iaus330.sciencesconf.org/). Poster presentation entitled: THE GAIA HR DIAGRAM OF S-TYPE STARS (Best poster prize) (S. SHETYE)

- **The impact of binaries on stellar evolution**, 03/07/2017 – 07/07/2017 (at ESO Garching) (https://www.eso.org/sci/meetings/2017/Imbase2017.html). Poster presentation entitled: THE GAIA HR DIAGRAM OF S-TYPE STARS (S. SHETYE)
- **FNRS Contact Group Astronomie & Astrophysique and Astronomy Day of the Royal Observatory of Belgium**, 18/09/2017 (Brussels) (http://www.planetarium.be/cg/index.htm). Oral presentation entitled: PROBING AGB NUCLEOSYNTHESIS VIA S STARS (S. SHETYE)
- **Connecting Observational and Theoretical Studies of AGB Stars (COASTARS Conference)**, 12/06/2017 - 16/06/2017 (Göteborg) (http://www.astro.uu.se/~coastars17/). Oral presentation entitled: HERSCHEL PACS AND SPIRE LIBRARY FOR AGB STARS AND RED SUPERGIANTS (D. NICOLAES)
- **Connecting Observational and Theoretical Studies of AGB Stars (COASTARS Conference)**, 12/06/2017 - 16/06/2017 (Göteborg) (http://www.astro.uu.se/~coastars17/). Oral presentation entitled: TRACING THE PHASE TRANSITION OF AL-BEARING SPECIES FROM MOLECULES TO DUST IN STELLAR WINDS (L. DECIN)
- **Astrochemistry** (IAU Symp. 332), March 2017 (Puerto Varas, Chile). Invited colloquium: MOLECULES AND DUST FORMATION IN LATE-TYPE STARS (L. DECIN)
- **EWASS2017,** session SS20, June 2017 (Prague). Talk: TRACING THE PHASE TRANSITION OF AL-BEARING SPECIES FROM MOLECULES TO DUST IN STELLAR WINDS (L. DECIN)
- **EWASS2017,** session SS18, June 2017 (Prague). Invited talk: TRACING THE PHASE TRANSITION OF AL-BEARING SPECIES FROM MOLECULES TO DUST IN STELLAR WINDS WITH METIS (L. DECIN)
- **EWASS2017,** session S16, June 2017 (Prague). Invited talk: STUDIES OF STELLAR EVOLUTION WITH ARCSEC IMAGING AND HIGH RESOLUTION SPECTROSCOPY (L. DECIN)
- University of Amsterdam, 2 October 2017. Invited colloquium: ON THE FORMATION OF EXTRATERRESTRIAL DUST GRAINS (L. DECIN)
- University of Nijmegen, 3 October 2017. Invited colloquium: ON THE FORMATION OF EXTRATERRESTRIAL DUST GRAINS (L. DECIN)
- **ERC-CoG AEROSOL meeting**, 12-13 September 2017 (Leuven). Organisation (L. DECIN)
- **Connecting Observational and Theoretical Studies of AGB Stars (COASTARS Conference)**, 12/06/2017 - 16/06/2017 (Göteborg) (http://www.astro.uu.se/~coastars17/). Oral presentation entitled: THE

PHOTODISSOCIATION OF CO IN CIRCUMSTELLAR ENVELOPES (M. GROENEWEGEN)

- **Connecting Observational and Theoretical Studies of AGB Stars (COASTARS Conference)**, 12/06/2017 - 16/06/2017 (Göteborg) (http://www.astro.uu.se/~coastars17/). Invited oral presentation entitled: KEEP CALM, AND RESOLVE STELLAR SURFACES (C. PALADINI)

- **72nd Netherlands Astronomy Conference**, 22/05/2017 – 24/05/2017 (Nijmegen) (http://www.astronomenclub.nl/conferentie/). Oral presentation entitled: THE EVOLUTIONARY NATURE OF RV TAU STARS WITH A DISC (R. MANICK)

- **The physics of evolved stars II**, 10/07/2017 – 13/07/2017 (Nice) (https://poe2017.sciencesconf.org/) Oral presentation entitled: THE EVOLUTIONARY NATURE OF RV TAU STARS WITH A DISC (R. MANICK)

- **IAU Symposium 330: Astrometry and Astrophysics in the Gaia sky**, 24/04/2017 – 28/04/2017 (Nice) (https://iaus330.sciencesconf.org/). Poster presentation entitled: TO BA OR NOT TO BA: THE FORMATION OF BARIUM STARS (A. JORISSEN)

- **The impact of binaries on stellar evolution**, 03/07/2017 – 07/07/2017 (at ESO Garching) (https://www.eso.org/sci/meetings/2017/Imbase2017.html). SOC member (S. VAN ECK)

2018:

- **XXXth General Assembly of the International Astronomical Union, IAU Symposium 343 "Why galaxies care about AGB stars?"**, Vienna (Austria), 19-26/08/2018 https://astronomy2018.univie.ac.at/
  Poster entitled BINARY INTERACTION ALONG THE RED GIANT BRANCH: THE BARIUM STAR PERSPECTIVE (A. ESCORZA)

- **Lorentz Center workshop: Weighing Stars from Birth to Death: How to Determine Stellar Masses?**, Leiden (The Netherlands), 19-23/11/2018 http://www.lorentzcenter.nl/lc/web/2018/1068/info.php3?wsid=1068&venue=Oort

  Attendance, active participation in the discussions, and contribution to the peer-reviewed publication about the workshop that will be submitted soon to "*The Astronomy and Astrophysics Review*" (A. ESCORZA)

- **XXXth General Assembly of the International Astronomical Union, IAU Symposium 343 "Why galaxies care about AGB stars?",** Vienna (Austria), 19-26/08/2018https://astronomy2018.univie.ac.at/

  Invited talk entitled SPECTROSCOPIC BINARIES AMONG AGB STARS FROM HERMES/MERCATOR (A. JORISSEN)

- **XXXth General Assembly of the International Astronomical Union,**

IAU Symposium 343 “Why galaxies care about AGB stars?”, Vienna (Austria), 19-26/08/2018 https://astronomy2018.univie.ac.at/
Contributed talk EVOLUTION AND NUCLEOSYNTHESIS OF S-TYPE STARS (S. SHETYE)

- **National Astronomy Conference 2018**, Groningen (The Netherlands), 14-16/03/2018 https://www.sron.nl/nac2018
Contributed talk EVOLUTION AND NUCLEOSYNTHESIS OF S-TYPE STARS (S. SHETYE)

- **Gaia ESO Survey meeting iDR6**, Florence (Italy), 30/05-01/06/2018, http://arcetri.astro.it/~sanna/ges/
Contributed talk STATISTICS OF SPECTROSCOPIC BINARIES IN GES IDR4/IDR5 (S. VAN ECK)

- **ESO workshop “A revolution in stellar physics with Gaia and large surveys”,** Warsaw (Poland), 03-07/09/2018 https://www.eso.org/sci/publications/announcements/sciann17092.html
Contributed talk S STARS AND S-PROCESS IN THE GAIA ERA (S. VAN ECK)

- **XXXth General Assembly of the International Astronomical Union, IAU Symposium 343 “Why galaxies care about AGB stars?”,** Vienna (Austria), 19-26/08/2018 (https://astronomy2018.univie.ac.at/). SOC member (H. VAN WINCKEL)

- **XXXth General Assembly of the International Astronomical Union, IAU Symposium 343 “Why galaxies care about AGB stars?”,** Vienna (Austria), 19-26/08/2018 https://astronomy2018.univie.ac.at/

  Poster entitled EXPLORING DUST MASS AND DUST PROPERTIES OF NEARBY AGB STARS (J. WIEGERT)

2019:

- **EWASS 2019,** Lyon, 23/06/2019,
Invited talk entitled BINARIES IN THE GAIA ERA (A. JORISSEN)

- **EWASS 2019**, Lyon, 23/06/2019,
Poster entitled AGB WINDS AS CONSTRAINT BY PACS AND SPIRE SPECTRA (M.A.T. GROENEWEGEN)

- **A Star has evolved: A conference in the honor of Hans Olofsson,** Smögen (Sweden), 27/08/2019,
Contributed talk entitled AGB WINDS AS CONSTRAINT BY PACS AND SPIRE SPECTRA (M.A.T. GROENEWEGEN)

6. PUBLICATIONS

Publications in refereed journals, ordered according to publication date (STARLAB consortium members are listed in bold face). Papers may be retrieved from institutional repositories at ULB (https://difusion.ulb.ac.be/), KU Leuven (https://limo.libis.be/primo-explore/search?vid=Lirias), or ROB (https://publi2-as.oma.be).

1. *HE 0017+0055 : A probable pulsating CEMP-rs star and long-period binary*
   A. Jorissen, T. Hansen, **S. Van Eck**, J. Andersen, B. Nordström, **L. Siess**, G. Torres, T. Masseron, **H. Van Winckel**, 2016,
   Astronomy & Astrophysics 586, A159 [WP2]
2. *To Ba or not to Ba: Enrichment in s-process elements in binary systems with WD companions of various masses*
   T. Merle, **A. Jorissen, S. Van Eck,** T. Masseron, **H. Van Winckel**, 2016,
   Astronomy & Astrophysics 586, A151 [WP1, WP2]
3. *Binary properties of CH and Carbon-Enhanced Metal-Poor stars*
   A. Jorissen, S. Van Eck, H. Van Winckel, T. Merle, H.M.J. Boffin, J. Andersen, B. Nordström, S. Udry, T. Masseron, L. Lenaerts, **C. Waelkens**, 2016,
   Astronomy & Astrophysics 586, A 158 [WP2]
4. *Hertzsprung – Russell diagram and mass distribution of barium stars*
   A. Escorza, H.M.J. Boffin, **A. Jorissen, S. Van Eck, L. Siess**, D . Pourbaix, **H. Van Winckel**, D. Karinkuzhi, **S. Shetye**, D. Pourbaix, 2017,
   Astronomy & Astrophysics, 608, A100 [WP2]
5. *Establishing binarity amongst Galactic RV Tauri stars with a disc,*
   R. Manick, H. Van Winckel, D. Kamath, M. Hillen, **A. Escorza,** 2017,
   Astronomy & Astrophysics 597, A129 (18 pp.) [WP2]
6. *SALT HRS discovery of a long-period double-degenerate binary in the planetary nebula NGC 1360*
   B. Miszalski, **R. Manick**, J. Mikołajewska, K. Iłkiewicz, D. Kamath, **H. Van Winckel**, 2018, Monthly Notices Royal Astronomical Society 473, 2275 – 2287 [WP2]
7. *When binaries keep track of recent nucleosynthesis : The Zr - Nb pair in extrinsic stars as a s-process diagnostic*
   D. Karinkuzhi, **S. Van Eck, A. Jorissen, S. Goriely, L. Siess,** T. Merle, **A. Escorza**, M. Van der Swaelmen, H.M.J. Boffin, T. Masseron, B. Plez, 2018,
   Astronomy & Astrophysics 618, A32 [WP1]
8. *Large granulation cells on the surface of the giant star* π^1 *Gruis*
   C. Paladini, F. Baron, **A. Jorissen**, J.-B. Le Bouquin, B. Freytag, **S. Van Eck**, J.-P. Berger, C. Siopis, A. Mayer, G. Sadowski, K. Kravchenko, **S. Shetye**, F. Kerschbaum, J. Kluska, S. Ramstedt, 2018,
   Nature 553, 310 (online December 21, 2017) (doi:10.1038/nature25001) [WP3]
9. *PACS and SPIRE range spectroscopy of cool, evolved stars*
   D. Nicolaes, M.A.T. Groenewegen, P. Royer, R. Lombaert, T. Danilovich, **L. Decin**, 2018, Astronomy & Astrophysics, Volume 618, A143, 42 pp. [WP3]
10. *S stars and s-process in the Gaia era. I. Stellar parameters and chemical abundances in a sub-sample of S stars with new MARCS model atmospheres,*
    S. Shetye, S. Van Eck, A. Jorissen, H. Van Winckel, L. Siess, S. Goriely, A. Escorza,

D. Karinkuzhi, B. Plez, 2018,
Astronomy & Astrophysics 620, A148 [WP1]

11. *Orbital properties of binary post-AGB stars,*
G.-M. Oomen, **H. Van Winckel**, O. Pols, G. Nelemans, **A. Escorza**, **R. Manick,** D. Kamath, C. Waelkens, 2018,
Astronomy & Astrophysics, Volume 620, A85, 21 pp. [WP2]
12. *SALT HRS Discovery of the Binary Nucleus of the Etched Hourglass Nebula MyCn 18*
B. Miszalski, **R. Manick**, J. Mikołajewska, **H. Van Winckel**, K. Iłkiewicz, 2018,
Publications of the Astronomical Society of Australia, Volume 35, e027, 11 pp. [WP2]
13. *SALT HRS discovery of a long-period double-degenerate binary in the planetary nebula NGC 1360*
B. Miszalski, **R. Manick,** J. Mikołajewska, K. Iłkiewicz, D. Kamath, **H. Van Winckel**, 2018,
Monthly Notices of the Royal Astronomical Society, Volume 473, pp. 2275-2287 [WP2]
14. *Constraining Convection in Evolved Stars with the VLTI*
C. Paladini, F. Baron, **A. Jorissen**, J.-B. Le Bouquin, B. Freytag, **S. Van Eck**, M. Wittkowski, J. Hron, A. Chiavassa, J.-P. Berger, C. Siopis, A. Mayer, G. Sadowski, K. Kravchenko, **S. Shetye**, F. Kerschbaum, J. Kluska, S. Ramsdedt, 2018,
The Messenger, 172, 24-26 [WP3]
15. *The perturbed sublimation rim of the dust disk around the post-AGB binary IRAS08544-4431*
J. Kluska, M. Hillen, **H. Van Winckel, R. Manick**, M. Min, S. Regibo, P. Royer, 2018,
Astronomy & Astrophysics, Volume 616, A153, 12 pp. [WP3]
16. *The evolutionary nature of RV Tauri stars in the SMC and LMC*,
R. Manick, H. Van Winckel, D. Kamath, S. Sekaran, K. Kolenberg, 2018,
Astronomy & Astrophysics 618, A21 [WP2]
17. *Variability in Proto-planetary Nebulae. V. Velocity and Light Curve Analysis of IRAS 17436+5003, 18095+2704, and 19475+3119*
B.J. Hrivnak, **G. Van de Steene, H. Van Winckel**, W. Lu, J. Sperauskas, 2018,
Astronomical Journal 156, 300 (21 pp.) [WP2]
18. *Spectroscopic and Photometric Variability of Three Oxygen Rich Post-AGB "Shell" Objects*
G. Van de Steene, B.J. Hrivnak, **H. Van Winckel**, J. Sperauskas, D. Bohlender , 2018,
Galaxies, 6, 131
19. *Barium and related stars, and their white-dwarf companions. II. Main-sequence and subgiant stars*
A. Escorza, D. Karinkuzhi, **A. Jorissen,** L. Siess, H. Van Winckel, D. Pourbaix, C. Johnston, B. Miszalski, G.-M. Oomen, M. Abdul-Masih, H.M.J. Boffin, P. North, R. Manick, S. Shetye, J. Mikołajewska, 2019,
Astronomy & Astrophysics 626, A128 [WP2]
20. *Barium and related stars, and their white-dwarf companions. II. Giant stars*
A. Jorissen, H.M.J. Boffin, D. Karinkuzhi, **S. Van Eck, A. Escorza**, **S. Shetye, H. Van Winckel,** 2019,
Astronomy & Astrophysics 626, A127 [WP2]
21. *Observational evidence of third dredge-up occurrence in 1 M_0 S-type stars*
S. Shetye, S. Goriely, S. Van Eck, A. Jorissen, L. Siess, H. Van Winckel, 2019,
Astronomy & Astrophysics 625, L1 [WP1]

22. *The spectroscopic binaries RV Tauri and DF Cygni*
R. Manick, D. Kamath, **H. Van Winckel, A. Jorissen,** S. Sekaran, D.M. Bowman, G.-M. Oomen, J. Kluska, D. Bollen, **C. Waelkens**, 2019,
Astronomy & Astrophysics 628, A40 [WP2]
23. *The post-common-envelope binary nucleus of the planetary nebula IC 4776: Neither an anomalously long orbital period nor a Wolf-Rayet binary*
B. Miszalski, **R. Manick , H. Van Winckel**, J. Mikołajewska, 2019,
MNRAS 487, 1040, 7pp. [WP2]
24. *Spectroscopic orbits of three dwarf barium stars*
P. North, **A. Jorissen, A. Escorza,** B. Miszalski, J. Mikolajewska, 2020,
The Observatory, in press [WP2]

Publications in conference proceedings

25. *S stars in the Gaia era: stellar parameters and nucleosynthesis*
S. Van Eck, D. Karinkuzhi, **S. Shetye, A. Jorissen, S. Goriely, L. Siess**, T. Merle, B. Plez, 2018,
Astrometry and Astrophysics in the Gaia sky, Proceedings of the International Astronomical Union, IAU Symposium 330, Cambridge University Press, pp. 352-353 [WP1]
26. *The TGAS HR diagram of S-type stars,*
S. Shetye, S. Van Eck, A. Jorissen, H. Van Winckel, L. Siess, 2018,
Astrometry and Astrophysics in the Gaia sky, Proceedings of the International Astronomical Union, IAU Symposium 330, Cambridge University Press, pp. 345-347 [WP1]

27. *The TGAS HR diagram of barium stars*
A. Escorza, H.M.J. Boffin, **A. Jorissen, L. Siess, S. Van Eck, S. Shetye,** D. Pourbaix, **H. Van Winckel**, 2018,
Astrometry and Astrophysics in the Gaia sky, Proceedings of the International Astronomical Union, IAU Symposium 330, Cambridge University Press, pp. 323-324 [WP2]

28. *Binary interaction along the Red Giant Branch: The Barium Star perspective*
A. Escorza, L. Siess, D. Karinkuzhi, H.M.J. Boffin, **A. Jorissen, H. Van Winckel**, 2019,
Why galaxies care about AGB stars?, Proceedings of the International Astronomical Union, IAU Symposium 343, Cambridge University Press, in press [WP2]
29. *Spectroscopic binaries among AGB stars from HERMES/Mercator: the case of V Hya,*
A. Jorissen, S. Van Eck, T. Merle, **H. Van Winckel**, 2019, Why galaxies care about AGB stars?, Proceedings of the International Astronomical Union, IAU Symposium 343, Cambridge University Press, in press [WP2]
30. *Probing stellar evolution with S stars and Gaia*
S. Shetye, S. Van Eck, A. Jorissen, H. Van Winckel, L. Siess, S. Goriely, 2019,
Why galaxies care about AGB stars?, Proceedings of the International Astronomical Union, IAU Symposium 343, Cambridge University Press, in press (arXiv:1810.07480) [WP1]
31. *Impact of binaries on stellar evolution in the Gaia era*

A. Jorissen
EWASS conference, June 2019
Mem. Soc. Astron. Ital., in press [WP2]

32. *The formation of barium stars as constrained by Gaia distances*
A. Escorza, A. Jorissen, H.M.J. Boffin
EWASS conference, June 2019
Mem. Soc. Astron. Ital., in press [WP2]

Publications in final stage of preparation

33. *Li-rich K giants, dust excess, and binarity*
A. Jorissen, H. Van Winckel, D. Pourbaix, A. Escorza, L. Siess, S. Van Eck, 2020, Astronomy & Astrophysics, submitted [WP2]
34. *Key nucleosynthesis diagnostics in CEMP-s and r/s stars*
D. Karinkuzhi, **S. Van Eck, S. Goriely, L. Siess, A. Jorissen, A. Escorza**, T. Merle, T. Masseron, **H. Van Winckel,** 2020
Astronomy & Astrophysics, submitted [WP1]
35. *How to disentangle geometry and mass-loss rate from AGB-star spectral energy distributions? The case of EP Aqr*
J. Wiegert, M.A.T. Groenewegen, A. Jorissen, L. Decin, T. Danilovich
Astronomy & Astrophysics, in preparation [WP3]

36. *The case for "trinsic" stars: revisiting the intrinsic/extrinsic S star paradigm*
S. Shetye, S. Van Eck, A. Jorissen, S. Goriely, L. Siess, A. Escorza, H. Van Winckel
Astronomy & Astrophysics, in preparation [WP1]
37. *S stars and s-process in the Gaia era II. Constraining the luminosity of the third dredge-up via Tc-rich S stars*
S. Shetye, S. Van Eck, A. Jorissen, S. Goriely, L. Siess, H. Van Winckel
Astronomy & Astrophysics, in preparation [WP1]
38. *Binary evolution along the Red Giant Branch with BINSTAR: The barium-star perspective*
A. Escorza, L. Siess, H. Van Winckel, A. Jorissen
Astronomy & Astrophysics, in preparation [WP2]

7. ACKNOWLEDGEMENTS

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ANNEXES

ENGLISH SUMMARY OF THE STARLAB PROJECT (MAX 3 PG):

RESEARCH AREA: STELLAR ASTROPHYSICS

CONTEXT. Stars in the mass range 0.8 – 8 M_{sun} (denoted low- and intermediate-mass stars – LIMS – in what follows) dominate the stellar population in our Milky Way Galaxy. During their ascent of the asymptotic giant branch (AGB) phase, LIMS are the siege of a rich nucleosynthesis, forging mainly carbon and elements heavier than iron through the so-called s-process. Because mixing processes bring these elements to their surface, the envelope composition of AGB stars is altered, and some of these stars will turn into carbon stars. As winds disperse the AGB envelope, molecules and dust grains form in a thick shell surrounding the star. As it expands, the circumstellar shell eventually merges with the interstellar medium where it releases the products of the stellar nucleosynthesis, thus contributing to the chemical evolution of the Galaxy.

Some specific families of LIMS are exclusively found among binary systems and the interaction between the stellar components can have a dramatic impact on both the internal structure and the surface chemical composition through the development of mixing processes (e.g thermohaline or rotationally-induced mixing) and exchange of nuclearly processed material between the stellar components.

Although the global evolution of stars is well understood, major uncertainties still affect our understanding of key physical and chemical processes. For instance, major shortcomings remain in the description of convection and internal mixing, mass loss, dust formation and gas-phase reactions in thick circumstellar shells, and, in case of binary systems, mass and angular-momentum transfer between the stellar components.

GOALS. The goal of this project is to boost our understanding of (some of) the physical and chemical processes at work in LIMS. Specifically, we plan

(i) to derive the surface abundances in specific LIMS and confront them with nucleosynthesis predictions. Progress is expected from the fact that we will use well-selected targets with known distances (like post-AGB stars in the Magellanic Clouds, and Galactic AGB stars with accurate Gaia parallaxes), allowing us to locate them in the Hertzsprung-Russell diagram, thus facilitating the confrontation with the models. The determination of the atmospheric composition of evolved LIMS provides strong diagnostics on the internal nuclear burning and mixing processes at play in the stellar interior. Owing to their rich nucleosynthesis, AGB and post-AGB stars are thus exceptional laboratories to test the robustness of stellar models.

(ii) to explore new binary evolutionary channels that may link classes of LIMS in binary systems (denoted LIMB in what follows). Progress is expected from the modeling of physical processes not dealt with so far (tidal interaction with a circumbinary disc for instance, to pump up the orbital eccentricity), and from the recent availability of a key diagnostic tool like the eccentricity – period diagram. The latter is obtained from our on-going effort to monitor the radial velocity of very diverse classes of LIMB to get their orbital elements. After 5 years of operation of our HERMES spectrograph, even wide orbits are now becoming available. Ultimately, this project should assess how the various classes of LIMB as well as their surface composition fit within a global picture.

(iii) to study the circumstellar shells around LIMS at different spatial scales using mid-IR interferometry and Herschel data. We will address questions related to the behaviour of mass-loss as a function of the geometry of the circumstellar shell.

STRATEGY. Our strategy is to confront model predictions and observational diagnostics by developing a close synergy between the project partners. On the observational side, the team has access to remarkable facilities (Herschel/ESA, PIONIER-VLTI/ESO, HERMES/Mercator – own instrument). These instruments offer excellent high-spectral resolution (or imaging) capabilities, with high sensitivity and large spectral coverage. The necessary data are available, and are still far from being fully exploited. Conversely, the rich possibilities which the current revolution in the observational methods enable, can only be fully exploited if their interpretation is based on advanced theoretical modeling. The team comprises experts on both advanced observational diagnostics and theoretical modeling. The rationale of this project is to enhance their interaction, so as to generate significant advances in our understanding of LIMS. Team members are experts in abundance determinations using MARCS and Turbospectrum softwares, in stellar-evolution and nucleosynthesis modeling using the STAREVOL and BINSTAR codes and in radiative-transfer modeling with tools such as RADMC-3D and DUSTY.

The expected impact of the project is (i) to provide better observational constraints on the nucleosynthesis and mixing processes at work in LIMS, (ii) unravel the links between specific families of LIMS exclusively found among binary systems, and identify the binary evolutionary channels through which these families arise, and (iii) better characterize the mass-loss properties of LIMS.

RESULTS. **Goal (i).** Abundances of heavy elements in stars of type S have shown that current stellar-evolution models correctly predict the onset of s-process nucleosynthesis in AGB stars and the transport of these nucleosynthesis products to the stellar surface. However, it was shown that the lower mass limit for this to occur is not 1.5 Msun, as previously thought, but rather 1 Msun. The predicted luminosity threshold for the onset of the s-process operation correctly separates intrinsic from extrinsic (i.e., binary) S stars. There are however a few mixed cases (extrinsic S stars that turned intrinsic when the secondary component enters the AGB phase) that were discovered in the studied sample. These mixed cases (that we call 'trinsic' S stars) were identified as binary Tc-rich and Nb-rich stars. In the usual situation, intrinsic S stars are Tc-rich and Nb-poor, whereas extrinsic S stars are Tc-poor and Nb-rich. A detailed comparison between observed and predicted abundances reveal that the usual s-process nucleosynthesis reproduces well the observed abundances in intrinsic S stars. On the contrary, some Carbon-Enriched Metal-Poor (CEMP) stars show signatures of the i-process of nucleosynthesis, requiring neutron densities intermediate between those of the s- and r-processes. By pushing to extreme values the parameters describing the mixing at work in AGB stars, our STAREVOL models are able to reproduce the observed i-abundance patterns.

Goal (ii). Thanks to an extensive radial-velocity monitoring program with the HERMES/Mercator spectrograph, eccentricity - period diagrams for several LIMB families could be obtained: dwarf and giant barium stars, subgiant and giant CH stars, extrinsic S stars, CEMP stars, post-AGB and post-RGB stars, RV Tau stars, sdB stars, central stars of planetary nebulae (CSPN). Among those, the shortest-period systems (a few days) are found among CSPN and dwarf CEMP stars, and likely result from Roche-lobe overflow and subsequent common-envelope evolution. The longest-period systems (~100 yr) mark the limit for efficient mass transfer by wind. These e - P diagrams are similar albeit not fully identical. For instance, there are puzzling differences between post-AGB and dwarf Ba stars (several short-period eccentric systems among the former not found among the latter), despite the fact that dwarf Ba systems are supposed to be the immediate progeny of post-AGB systems. But strangely, RV Tau systems seem to be lacking orbits with periods shorter than 700 d, which are frequent among post-AGB systems, despite the fact that RV Tau systems may be considered as post-AGB systems in a wider sense. We have quantitatively studied the evolutionary link between barium dwarfs and giants, and concluded that the tidal effects operating on the red giant branch account for the presence of more eccentric systems at short periods (< 1000 d) among the dwarf barium stars. The mass distribution of the companions to barium stars has been derived and confirms that they must likely be white dwarfs, as predicted by the binary evolutionary scenario.

Goal (iii). An image of the surface features of the S star π1 Gru been obtained with VLTI/PIONIER data, revealing spots, likely of convective origin. These surface inhomogeneities could be the seed for the asymmetries seen in the wind.

An extensive list of molecular and atomic spectral features has been built from Herschel PACS and SPIRE spectra that will be helpful for diagnosing the physical conditions characterizing the CS of AGB stars.

We have shown that the knowledge of the circumstellar-shell (CS) geometry (i.e., spiral, disc, or sphere) is mandatory in order to derive their dust masses in a accurate way (i.e., better than within a factor of 100!).

KEYWORDS (MAX 5):

Circumstellar shells, abundances and nucleosynthesis, binary systems, mass loss, stellar structure and evolution

NEDERLANDSE SAMENVATTING VAN DE STARLAB PROJECT (MAX 3 PG):

ACHTERGROND. Sterren met massa tussen 0,8 en 8 M_{zon} (hierna "lage en middelgrote massa sterren" - LIMS - genoemd) domineren de stellaire populatie van onze Melkweg. Tijdens hun Asymptotische Reuzentak fase (AGB) vindt er in de LIMS een rijke nucleosynthese plaats, het zogenaamde “s-process”, waarin voornamelijk koolstof en elementen die zwaarder zijn dan ijzer worden geproduceerd. Door convectie worden deze elementen naar het oppervlak gebracht, waardoor de chemische samenstelling aan het steroppervlak gewijzigd wordt, en sommige van deze sterren zelfs koolstofsterren worden. Terwijl een stellaire wind de buitenste lagen van de AGB-ster doet uitdijen, worden er moleculen en stofkorrels gevormd waardoor een dik omhulsel de ster omgeeft. Naarmate dit circumstellaire omhulsel verder expandeert, verdunt het geleidelijk, en vermengen de producten van de stellaire nucleosynthese zich met het interstellaire medium, waardoor de chemische evolutie van het Melkwegstelsel beïnvloed wordt.

Sommige specifieke soorten van LIMS bestaan uitsluitend uit binaire systemen. De interactie tussen de twee componenten van een dubbelster kan een aanzienlijke invloed hebben op hun interne structuur en chemische samenstelling. Door middel van mengprocessen (veroorzaakt door bijvoorbeeld temperatuurverschillen en rotatie) en de uitwisseling van massa, verrijkt met de in de nucleosynthese geproduceerde elementen, tussen de stellaire componenten, kan hun interne structuur en chemische samenstelling veranderd worden.

Hoewel de algemene evolutie van sterren goed wordt begrepen, zijn er nog grote onzekerheden die onze kennis van enkele belangrijke fysische en chemische processen beperken. Zo blijven er grote lacunes bestaan in de beschrijving van convectie en interne mengprocessen, massaverlies, stofvorming en gasreacties in de dikke circumstellaire schillen en, in het geval van binaire systemen, de overdracht van massa en impulsmoment tussen de stellaire componenten.

DOELSTELLINGEN: Het doel van dit project is het verbeteren van ons begrip van (sommige) fysische en chemische processen die in de LIMS aan het werk zijn. Concreet hadden we van plan om:

(i) de oppervlaktesamenstelling van specifieke LIMS te bepalen en deze te vergelijken met de voorspellingen van de modellen van nucleosynthese. Vooruitgang wordt verwacht van het feit dat we gebruik zullen maken van goed gekozen sterren met bekende afstanden (zoals post-AGB sterren in de Magellaanse Wolken en Galactische AGB sterren met exacte Gaia parallaxen), waardoor we hun plaats in het Hertzsprung-Russell diagram kunnen bepalen en vergelijken met de berekende modellen. Het bepalen van de atmosferische samenstelling van geavanceerde LIMS zorgt voor een robuuste diagnostiek van interne nucleaire verbrandings- en mengprocessen die in het inwendige van de sterplaats vinden. Wegens hun rijke nucleosynthese zijn AGB- en post-AGB-sterren uitzonderlijke laboratoria voor het testen van de robuustheid van stellaire modellen.

(ii) het verkennen van nieuwe mogelijke paden waarlangs binaire systemen tussen de verschillende klassen van LIMS zouden kunnen evolueren (hierna LIMB genoemd). Er wordt vooruitgang verwacht door het modelleren van fysische processen die tot nu toe niet in rekening werden gebracht (bv. getijdeninteractie met een circumbinaire schijf om de excentriciteit van de baan te verhogen), en door het gebruik van het nieuw verkregen excentriciteit-periode (e - P) diagram in de analyse. Dit laatste werd bepaald uit onze jarenlange metingen van de radiale snelheid en de bepaling van de orbitale elementen van zeer uiteenlopende klassen van LIMB. Na 10 jaar waarnemen met de HERMES-spectrograaf, zijn nu zelfs de langste omloopbanen beschikbaar. Uiteindelijk moet dit project het mogelijk maken om te evalueren hoe de verschillende klassen van LIMB en hun oppervlaktesamenstelling passen in een globaal schema.

(iii) het bestuderen van de circumstellaire schillen op verschillende schalen rond LIMS met behulp van gegevens van de infraroodsatelliet Herschel en mid-IR interferometrie. In het bijzonder zullen we voor verschillende geometrieën van de circumstellaire schil de intensiteit en de aard van het massaverlies bepalen.

STRATEGIE. Onze strategie is om de voorspellingen van de modellen te confronteren met observationele kenmerken door het ontwikkelen van een nauwe synergie tussen de projectpartners. Op het vlak van waarnemingen beschikt het team over opmerkelijke telescopen en instrumenten (Herschel/ESA, PIONIER-VLTI/ESO, HERMES/Mercator/KU Leuven). Deze instrumenten bieden uitstekende mogelijkheden voor spectroscopie (of beeldvorming) met een hoge spectrale resolutie, met een grote gevoeligheid en een breed spectraal bereik. De noodzakelijke gegevens zijn beschikbaar en worden nog lang niet volledig benut. Omgekeerd kunnen de ruime mogelijkheden die de huidige waarnemingsmethodes bieden alleen ten volle worden benut als hun interpretatie gebaseerd is op geavanceerde theoretische modellen. Het team bestaat uit deskundigen op het gebied van waarnemingsmethoden en theoretische modellering. De ambitie van dit project is om hun samenwerking te verhogen om zo belangrijke vooruitgang te genereren in ons begrip van LIMB. De teamleden zijn experts in het bepalen van de abundantie van chemische elementen met behulp van MARCS en Turbospectrum software, in het modeleren van stellaire evolutie en nucleosynthese met behulp van STAREVOL en BINSTAR codes, en in het modeleren van stralingsoverdracht met behulp van software programma's zoals RADMC-3D en DUSTY.

De impact verwacht van het project is (i) het bepalen van betere observationele limieten op nucleosynthese en mengprocessen in LIMS, (ii) het ontrafelen van de evolutionaire verbanden tussen de specifieke families van LIMS die uitsluitend onder binaire systemen voorkomen en het bepalen van de evolutionaire paden waarlangs deze families ontstaan, en (iii) het beter karakteriseren van het massaverlies van de LIMS.

RESULTATEN. **Doelstelling (i).** De hoeveelheid van zware elementen in S-type sterren heeft aangetoond dat de huidige modellen van stellaire evolutie het begin van de nucleosynthese van het s-proces in AGB-sterren en het transport van deze nucleosynthese producten naar het stellaire oppervlak correct voorspellen. Dit project heeft echter aangetoond dat de onderste massalimiet hiervoor niet 1,5 M_{zon} is, zoals eerder gedacht, maar 1 M_{zon}. De voorspelde helderheidslimiet voor de aanvang van het s-proces en die intrinsieke en extrinsieke (d.w.z. binaire) S-sterren scheidt, is correct. Er zijn echter enkele gemengde gevallen (extrinsieke S-sterren die intrinsiek zijn geworden wanneer de secundaire component op zijn beurt de AGB-fase ingaat) ontdekt onder de bestudeerde objecten. Deze gemengde gevallen (die we "intrinsieke" S-sterren noemen) zijn geïdentificeerd als Tc- en Nb-rijke dubbelsterren. In de gebruikelijke situatie zijn intrinsieke S-sterren rijk aan Tc en arm aan Nb, terwijl extrinsieke S-sterren arm zijn aan Tc en rijk aan Nb. Een gedetailleerde vergelijking tussen de geobserveerde en de voorspelde hoeveelheid van deze elementen toont aan dat de gebruikelijke nucleosynthese van het proces de geobserveerde abundantie in intrinsieke S-sterren goed nabootst. Integendeel, sommige CEMP-sterren (genaamd "CEMP-rs sterren" waar CEMP het acroniem is van "Koolstof verrijkt en Metaal-arm") tonen kenmerken van het i-proces, waarvoor neutronendichtheden nodig zijn die tussen die van de s- en r-processen in liggen. Door extreme waarden voor de parameters die de mengprocessen in AGB-sterren beschrijven te gebruiken, zijn onze STAREVOL-modellen in staat om de i-proces abundanties die in deze CEMP-sterren worden waargenomen, te reproduceren.

Doelstelling (ii). Dankzij een uitgebreid programma voor het monitoren van radiale snelheden met behulp van de HERMES/Mercator-spectrograaf konden excentriciteit-periode (e - P) diagrammen voor verschillende LIMB-families worden verkregen: dwerg- en reuzen-barium sterren, sub-reuzen- en reuzen-CH-sterren, extrinsieke S-sterren, CEMP-sterren, post-AGB- en post-RGB-sterren, RV Tau-sterren, sdB-sterren en centrale sterren van de planetaire nevels (CSPN). De systemen met zeer korte perioden (enkele dagen), waaronder CSPN-sterren en CEMP-dwergsterren, zijn waarschijnlijk het gevolg van Rochelobe transfer en de daaropvolgende evolutie binnen het gemeenschappelijk omhulsel. Systemen met de langste periodes (~100 jaren) bepalen de grens van efficiënte massaoverdracht door de wind van de AGB-ster. De e–P diagrammen van de verschillende families van LIMB's lijken op elkaar, maar zijn niet volledig identiek. Zo zijn er bijvoorbeeld verrassende verschillen tussen post-AGB sterren en dwerg Ba-sterren (bv. er worden wel post-AGB sterren gevonden met korte periode, maar geen dwerg Ba-sterren), ondanks het feit dat verondersteld wordt dat post-AGB evolueren naar dwerg Ba-sterren. Aan de andere kant lijken RV Tau-systemen merkwaardig genoeg geen omloopbanen te hebben met perioden van minder dan 700 dagen, wat toch vaak voorkomt bij post-AGB-systemen, ondanks het feit dat RV Tau-systemen eigenlijk als post-AGB-systemen worden beschouwd. We hebben een kwantitatieve studie uitgevoerd naar het evolutionaire verband tussen dwerg Ba-sterren en reuzen Ba-sterren. We concludeerden dat getijde-effecten op de rode reuzentak de aanwezigheid van meer excentrische systemen met korte perioden (< 1000 d) onder bariumdwergsterren verklaren. De massaverdeling van de begeleiders van bariumsterren werd verkregen en bevestigt dat deze begeleider naar alle waarschijnlijkheid witte dwergsterren zijn, zoals voorspeld door het binaire evolutiescenario.

Doelstelling (iii). Een beeld van het oppervlak van de ster Sπ1 Gru is verkregen met VLTI/PIONIER-waarnemingen. Dit beeld onthult de aanwezigheid van vlekken, waarschijnlijk van convectieve oorsprong. Deze inhomogeniteit op het oppervlak zouden kunnen aan de basis liggen van de asymmetrische wind.

Op basis van de Herschel PACS en SPIRE spectra is een uitgebreide lijst van identificaties van moleculaire en atomaire spectrale lijnen gemaakt. Deze zullen nuttig zijn om de typische fysische kenmerken van circumstellaire schillen van AGB-sterren te bepalen.

We hebben aangetoond dat kennis van de geometrie van de circumstellaire schillen (d.w.z. spiraal, schijf of sferisch) een vereiste is om het stofgehalte nauwkeurig te kunnen afleiden (d.w.z. beter dan een factor 100 op de verhouding gasmassa/stofmassa).

RÉSUMÉ EN FRANÇAIS DU PROJET STARLAB:

CONTEXTE. Les étoiles de masse comprise entre 0,8 et 8 Msol (désignées par "étoiles de masse faible et intermédiaire" - LIMS - dans ce qui suit) dominent la population stellaire de notre Galaxie, la Voie Lactée. Pendant leur ascension de la branche géante asymptotique (AGB), les LIMS sont le siège d'une riche nucléosynthèse, forgeant principalement du carbone et des éléments plus lourds que le fer par un processus nucléosynthétique appelé "processus s". Comme les processus de mélange amènent ces éléments à la surface des étoiles AGB, la composition de l'enveloppe de ces étoiles est modifiée, et certaines d'entre elles se transforment alors en étoiles carbonées. Lorsque les vents dispersent l'enveloppe de l'étoile AGB, des molécules et des grains de poussière se forment dans une épaisse coquille entourant l'étoile. En se dilatant, la coquille circumstellaire se dilue peu à peu dans le milieu interstellaire où elle libère les produits de la nucléosynthèse stellaire, contribuant ainsi à l'évolution chimique de la Galaxie.

Certaines familles spécifiques de LIMS se trouvent exclusivement parmi les systèmes binaires. L'interaction entre les deux composantes d'un système binaire peut avoir un impact considérable sur la structure interne et la composition chimique de surface, par le truchement de processus de mélange (par exemple, le mélange thermohaline ou celui induit par rotation) et l'échange des produits de nucléosynthèse entre les composantes stellaires.

Bien que l'évolution générale des étoiles soit bien comprise, des incertitudes majeures affectent encore notre compréhension de certains processus physiques et chimiques déterminants. Par exemple, des lacunes majeures subsistent dans la description de la convection et du mélange interne, de la perte de masse, de la formation de poussière et des réactions en phase gazeuse dans les épaisses coquilles circumstellaires et, dans le cas des systèmes binaires, du transfert de masse et de moment angulaire entre les composantes stellaires.

OBJECTIFS. Le but de ce projet est d'améliorer notre compréhension de (certains) des processus physiques et chimiques à l'œuvre dans les LIMS. Plus précisément, nous prévoyons

(i) de dériver les abondances de surface dans des LIMS spécifiques et de les confronter aux prévisions de nucléosynthèse. Des progrès sont attendus du fait que nous utiliserons des cibles bien choisies avec des distances connues (comme les étoiles post-AGB dans les Nuages de Magellan, et les étoiles AGB galactiques avec des parallaxes Gaia précises), ce qui nous permettra de les localiser dans le diagramme de Hertzsprung-Russell, facilitant ainsi la confrontation avec les modèles. La détermination de la composition atmosphérique des LIMS évoluées fournit des diagnostics solides sur les processus internes de combustion nucléaire et de mélange en jeu dans l'intérieur de l'étoile. Grâce à la richesse de leur nucléosynthèse, les étoiles AGB et post-AGB sont donc des laboratoires exceptionnels pour tester la robustesse des modèles stellaires.

(ii) d'explorer de nouveaux canaux évolutifs binaires qui pourraient relier des classes de LIMS dans des systèmes binaires (désignés LIMB dans ce qui suit). Des progrès sont attendus grâce la modélisation de processus physiques non traités jusqu'à présent (interaction de la marée avec un disque circumbinaire par exemple permettant d'augmenter l'excentricité de l'orbite), et grâce à la contrainte fournie par le diagnostic-clé que constitue le

diagramme excentricité - période. Ce dernier est obtenu grâce à nos mesures de longue date de la vitesse radiale de classes très diverses de LIMB afin d'obtenir leurs éléments orbitaux. Après 10 ans d'opérations de notre spectrographe HERMES, même les orbites les plus longues sont maintenant disponibles. En fin de compte, ce projet devrait permettre d'évaluer comment les diverses classes de LIMB ainsi que la composition de leur surface s'inscrivent dans un schéma global.

(iii) d'étudier les coquilles circumstellaires autour des LIMS à différentes échelles spatiales en utilisant les données du satellite infrarouge Herschel. Nous aborderons en particulier les questions relatives au comportement de la perte de masse en fonction de la géométrie de la coquille circumstellaire.

STRATÉGIE. Notre stratégie est de confronter les prédictions des modèles aux diagnostics observationnels en développant une étroite synergie entre les partenaires du projet. Du côté observationnel, l'équipe dispose de moyens remarquables (Herschel/ESA, PIONIER-VLTI/ESO, HERMES/Mercator/KU Leuven). Ces instruments offrent d'excellentes capacités de haute résolution spectrale (ou d'imagerie), avec une grande sensibilité et une large couverture spectrale. Les données nécessaires sont disponibles, et sont encore loin d'être pleinement exploitées. A l'inverse, les riches possibilités qu'offrent les moyens d'observation actuels ne peuvent être pleinement exploitées que si leur interprétation est basée sur une modélisation théorique de pointe. L'équipe est composée d'experts en méthodes observationnelles et en modélisation théorique. L'ambition de ce projet est d'améliorer leur interaction, afin de générer des avancées significatives dans notre compréhension des LIMS. Les membres de l'équipe sont experts en détermination d'abondance à l'aide des logiciels MARCS et Turbospectrum, en modélisation de l'évolution stellaire et de la nucléosynthèse à l'aide des codes STAREVOL et BINSTAR, et en modélisation du transfert radiatif grâce aux outils tels que RADMC-3D et DUSTY.

L'impact attendu du projet est (i) de fournir de meilleures contraintes d'observation sur les processus de nucléosynthèse et de mélange à l'œuvre dans les LIMS, (ii) de démêler les liens entre les familles spécifiques de LIMS que l'on trouve exclusivement parmi les systèmes binaires, et d'identifier les canaux évolutifs binaires par lesquels ces familles sont formées, et (iii) de mieux caractériser les propriétés de perte de masse des LIMS.

RÉSULTATS. **Objectif (i).** Les abondances d'éléments lourds dans les étoiles de type S ont montré que les modèles actuels d'évolution stellaire prédisent correctement le début de la nucléosynthèse du processus s dans les étoiles AGB et le transport de ces produits de nucléosynthèse vers la surface stellaire. Cependant, ce projet a montré que la limite inférieure de masse pour que cela se produise n'est pas de 1,5 Msol, comme on le pensait précédemment, mais plutôt de 1 Msol. Le seuil de luminosité prédit pour le début de l'opération du processus s sépare correctement les étoiles S intrinsèques et extrinsèques (c.-à-d. binaires). Il y a cependant quelques cas mixtes (étoiles S extrinsèques qui sont devenues intrinsèques lorsque la composante secondaire entre à son tour dans la phase AGB) qui ont été découverts dans l'échantillon étudié. Ces cas mixtes (que nous appelons étoiles S " trinsèques") ont été identifiés comme des étoiles binaires riches en Tc *et* en Nb. Dans la situation habituelle, les étoiles S intrinsèques sont riches en Tc et pauvres en Nb, alors que les étoiles S extrinsèques sont pauvres en Tc et riches en Nb. Une comparaison détaillée entre les abondances observées et prédites révèle que la nucléosynthèse habituelle du processus s reproduit bien les abondances observées dans les étoiles S intrinsèques. Au contraire, certaines étoiles CEMP (appelées "étoiles CEMP-rs" où CEMP est l'acronyme de "Carbon-Enriched Metal-Poor") montrent des signatures du processus i de nucléosynthèse, nécessitant des densités neutroniques intermédiaires entre celles des processus s et r. En poussant à des valeurs extrêmes les paramètres décrivant le mélange à l'oeuvre dans les étoiles AGB, nos modèles STAREVOL sont capables de reproduire les profils d'abondances observés dans ces étoiles CEMP-rs.

Objectif (ii). Grâce à un vaste programme de surveillance de la vitesse radiale au moyen du spectrographe HERMES/Mercator, des diagrammes excentricité - période (e - P) pour plusieurs familles de LIMB ont pu être obtenus : étoiles naines et géantes à baryum, étoiles sous-géantes et géantes CH, étoiles S extrinsèques, étoiles CEMP, étoiles post-AGB et post-RGB, étoiles RV Tau, étoiles sdB, étoiles centrales de nébuleuses planétaires (CSPN). Parmi celles-ci, les systèmes aux très courtes périodes (quelques jours) se trouvent parmi les étoiles CSPN et les étoiles naines CEMP, et résultent probablement du débordement du lobe de Roche et de l'évolution ultérieure de l'enveloppe commune. Les systèmes aux plus longues périodes (~100 ans) marquent la limite d'un transfert de masse efficace par le vent de l'étoile AGB. Les diagrammes e - P de ces différentes familles de LIMB sont similaires bien qu'ils ne soient pas totalement identiques. Il y a par exemple des différences étonnantes entre les étoiles post-AGB et les étoiles Ba naines (plusieurs systèmes excentriques de courte période parmi les premiers ne se retrouvent pas parmi les seconds), malgré le fait que les étoiles Ba naines sont censées être les progénitures immédiates des systèmes post-AGB. D'autre part, les systèmes RV Tau semblent curieusement manquer d'orbites avec des périodes inférieures à 700 j, qui sont pourtant fréquentes parmi les systèmes post-AGB, malgré le fait que les systèmes RV Tau peuvent être considérés comme des systèmes post-AGB au sens large. Nous avons réalisé une étude quantitative du lien évolutif entre les étoiles naines à baryum et les étoiles à baryum géantes. Nous en avons conclu que les effets de marée opérant sur la branche des géantes rouges expliquent la présence de systèmes plus excentriques à courtes périodes (< 1000 j) parmi les étoiles naines à baryum. La distribution de masse des compagnons des étoiles à baryum a été obtenue et confirme que ces compagnons sont selon toute vraisemblance des étoiles naines blanches, comme le prévoit le scénario d'évolution binaire.

Objectif (iii). Une image de la surface de l'étoile S π1 Gru a été obtenue grâce à des observations VLTI/PIONIER. Cette image révèle la présence de taches, probablement d'origine convective. Ces inhomogénéités de surface pourraient être à l'origine des asymétries observées dans le vent.

Une liste extensive de raies spectrales moléculaires et atomiques a été construite à partir des spectres Herschel PACS et SPIRE. Celles-ci seront utiles pour diagnostiquer les conditions physiques caractérisant les coquilles circumstellaires d'étoiles AGB.

Nous avons montré que la connaissance de la géométrie de la coquille circumstellaire (c.-à-d. spirale, disque ou sphère) est obligatoire pour dériver leur contenu en poussière de façon précise (c.-à-d. à mieux qu'un facteur 100 sur le rapport masse de gaz / masse de poussières).