ENGLISH SUMMARY OF THE STARLAB PROJECT:

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:

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