POST-AGB STARS IN THE LMC AND SMC AS TRACERS OF STELLAR EVOLUTION

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Abstract: The chemical diversity displayed by Galactic post-AGB stars is much larger than anticipated, but the theoretical interpretation is hampered by a general lack of accurate distances and hence luminosities. We initiated therefore a large project to find and study optically bright post-AGB stars in the Large and Small Magellanic clouds. In this contribution we give a short overview on the chemical diversity in the Galactic sample and a status report of our LMC and SMC project. We highlight a few detailed studies of individual sources to illustrate the scientific potential of finding and studying extra-galactic post-AGB stars.

Keywords: Stars: AGB and post-AGB; Stars: abundances; Stars: binaries: spectroscopic; Surveys

1. Introduction

The final evolution of low- and intermediate-mass stars is a rapid transition from the Asymptotic Giant Branch (AGB) over the post-AGB transit towards the Planetary Nebula Phase (PN), before the stellar remnant cools down as a White Dwarf (WD). Although this scheme may be generally acknowledged, there is no understanding from first principles of different important physical processes that govern these evolutionary phases. The main shortcomings are related to the lack of understanding of the mass-loss mechanisms and mass-loss evolution along the AGB ascent (e.g. [23]), the subsequent shaping processes of the circumstellar shells (e.g. [8]) and the lack of fundamental understanding of the internal chemical evolution of these stars (e.g. [21]). In this contribution we will concentrate on the latter and focus on the internal chemical evolution of AGB stars. Two particular uncertainties in AGB evolution are (a) the 3rd dredge-up phenomenon, during which products of the internal nucleosynthesis are brought to the surface of the star, and (b) the slow neutron capture process (s-process)
itself. The s-process in AGB stars is an important contributor to cosmic abundances past the iron peak. Additionally, these stars are also thought to be very important contributors to the total carbon and nitrogen enrichment of galaxies.

In recent years, the theoretical models of the internal nucleosynthesis and photospheric enrichment processes in AGB stars have gained enormously in sophistication: extensive nuclear networks with updated cross-sections have been included (e.g. [18], [7], [29], [33], [20]); non-convective mixing due to differential rotation and thermohaline mixing have been implemented (e.g. [43], [44], [1], [36]); the effects of deep mixing or extra mixing processes have been critically evaluated (e.g. [29], [5]); and overshoot regimes have been explored in more detail in order to explain the extent of the $^{13}$C pocket.

All these processes involve great uncertainties and observational data are required to calibrate them. These observational tests remain, however, quite limited (e.g. [21]). As a consequence, large uncertainties still remain on e.g.: the mixing regimes and their influence on the photospheric abundances; the overshoot parameters related to the creation of the $^{13}$C pocket; the relevance of extra mixing schemes along the whole evolutionary tracks; the integrated mass-loss on the AGB and the metallicity dependence of all these parameters. In these proceedings we show that detailed chemical studies of post-AGB stars can yield important observational tests to these predictions.

Optical spectra of post-AGB stars are ideally suited to study the surface composition (e.g.[48]). First their atmospheres do not show the large amplitude pulsations as well as the large mass-loss rates that characterize evolved AGB atmospheres. Second, their photospheres are hotter, so atomic transitions prevail, while molecular veiling dominates in AGB photospheres. This allows one to quantify the abundance in post-AGB star for a very wide range of elements, from CNO up to the most heavy s-process elements, well beyond the Ba peak (e.g [40]). But post-AGB stars evolve on a very fast track and they are rare as a consequence (e.g.[45] also http://www.ncac.torun.pl/postagb2). In this contribution we will illustrate the unexpected large chemical diversity of the Galactic sources in Section 2. This inspired us to launch a large project to study systematically the optically bright post-AGB stars in the Magellanic Clouds and we introduce the
ongoing project in Section 3. Section 4 is then devoted to some detailed results of individual objects. We end this contribution with a short summary.

2. **Galactic s-process Enriched Post-AGB Stars**

2.1. **The 21 µm post-AGB stars**

The 21 µm circumstellar dust feature was discovered in low resolution IRAS spectra [31]. Till now the carrier of the dust feature remains disputed, but it is clear that it is only rarely observed: it has been discovered only in about 20 Galactic stars (e.g. [6], [25]). The dust feature is exclusively found around post-AGB stars which are carbon-rich.

All 21 µm stars which are studied in detail show a rich spectrum which are often really dominated by atomic transitions of s-process elements, despite the fact that the number densities even after enrichment are not large. These objects have sub-solar metallicities indicating they are formed from stars with a low initial mass. They are among the most s-process enriched objects known to date (e.g. [51], [42], Fig.1). They display a wide variety in s-process efficiencies, which are usually described as the abundance ratio between the heavy s-process elements around the Ba-peak ([ls/Fe]) and the light s-process elements around the Sr peak ([ls/Fe]). Other strongly enhanced objects exist e.g. [41], but it is unclear whether these are 21 µm sources, as no infrared spectra are available.

Figure 1. Abundance patterns in some Galactic 21 µm post-AGB stars [42].
Other Galactic post-AGB stars are not enriched and there are relatively few objects known that show only a very mild s-process enhancement ([48], [37]). The non-enriched objects do cover the same metallicity range between solar and about [Fe/ H] = −1.3. It is unclear whether there is a systematic luminosity difference between the enriched and non-enriched objects, as the distances are largely unknown.

2.2. Galactic diversity: chemical depletion

A very specific photospheric anomaly is called photospheric depletion: the abundance patterns show a clear correlation with the condensation temperature of the element (Fig.2). The photospheric content reflects the gas-phase abundance of the interstellar medium (ISM): refractory elements are underabundant while volatile elements are not. In Galactic post-AGB stars, this anomaly is surprisingly common (e.g. [16], [34], [24], [37], [49] and references therein).

Figure 2. Depleted atmosphere as observed in IRAS11472-0800 [49].
The presence of this abundance pattern is well correlated with specific SED characteristics (with some noticeable exceptions): the objects display a clear near-infrared excess indicating that circumstellar dust must be close to the central star. This indicates that a stable disc is present [9]. The very compact nature of the hot dust means that interferometric observations are needed to resolve them (e.g. [12], [13], [22]). The longevity of the circumstellar material is corroborated by the systematic presence of highly processed (crystalline) large grains (e.g. [14]), again typical for dusty discs. That the discs are indeed in rotation was first found in the Red Rectangle [3] and now even spectacularly resolved with the ALMA array [4] in the same object. A survey using single dish observations shows rotation is indeed widespread [2]. Many of the RV Tauri stars (luminous population II Cepheids) show both depletion patterns as well as disc SEDs.

The first depleted objects were found to be binaries [52], and hence we launched a large radial velocity monitoring campaign using our own HERMES spectrograph [38] on the 1.2m Mercator telescope. Our radial velocity monitoring campaigns are still ongoing but we can safely conclude that we indeed found the suspected high binary rate with periods between 100 and 2000 days ([50], [19]). The systems are now not in contact, but the orbits are too short to have accommodated an AGB star. Many orbits are surprisingly eccentric which by itself is not understood as the tides should have circularised the orbits on the giant branches.

The global picture that emerges is therefore that a binary star evolved in a system that is too short to accommodate a full-grown AGB star. During a badly understood phase of strong interaction, a circumbinary dusty disc was formed, but the binary system did not suffer dramatic inspiral. What we observe now is an F-G supergiant in a binary system, which is surrounded by a circumbinary dusty disc in a bound orbit. The formation, structure, and evolution of the disc is far from being understood, but it does appear to be a key ingredient in our understanding of the late evolution of a very significant binary population. The disc evolution will determine the infrared lifetime of these objects. The disc seems to be a prerequisite to obtain the photospheric depletion patterns by accretion of gas [54], cleaned from refractories by dust formation but there is no detailed understanding of the whole process yet.
The main problem in relating the observational diversity to evolutionary channels is that for the majority of Galactic post-AGB stars, the distances are poorly known. The lack of luminosities prevents a good interpretation, as we cannot place objects accurately in the HR diagram.

3. Finding Post-AGB Stars in the Magellanic Clouds

By virtue of their spectral types, favourable bolometric corrections and especially their constrained distances, post-AGB stars in external galaxies offer now unprecedented tests for AGB theoretical structure and enrichment models of low- and intermediate-mass stars.

Systematic searches of the rare objects in external galaxies only became possible after the release of deep infrared surveys. We exploited the release of the infrared LMC SAGE-Spitzer survey, which includes about 6.4 million infrared sources [35]. We searched for luminous, optically bright stars with infrared colours indicative of a past history of heavy dusty mass loss. To probe the spectral types of the central objects, we first obtained single-shot low-resolution optical spectra at Siding Spring, Australia, and at SAAO (South-Africa). Our initial result consists of some 1400 good candidate post-AGB stars, of which 70 are well characterised with low-resolution spectra at that stage [47]. About half of the objects in our sample of LMC post-AGB candidates show a spectral energy distribution (SED) that is indicative of a disc rather than an expanding and cooling AGB remnant. Like in the Galaxy, the disc sources are likely associated with binary evolution.

For the SMC, with its lower global metallicity, the third dredge-up enrichment is predicted to be stronger, as witnessed by the low luminosity of the intrinsic Carbon star luminosity function of the SMC [32]. The sample selection of the SMC was based on the SAGE-SMC catalogue [17] in a very similar way as was performed on the LMC data. Realising the importance of the spectral characterisation of the central objects, we requested and obtained telescope time on the AAOmega-2dF multifibre spectrograph at the AAT in Australia (Fig. 3). This unique instrument with a large field of view deploys over 390 fibres, and allowed for a very efficient coverage of the complete LMC and SMC galaxies.
Figure 3. The SMC with the different settings of the 2dF spectrograph [26].

With these spectra, we cleaned the candidates from all contaminants (PNe, background galaxies, quasars, Carbon stars, M-stars and young stellar objects) and finalised our sample of post-AGB stars. Reference [26] developed a spectral typing pipeline to match each individual spectrum to a vast library of synthetic templates. With the atmospheric parameters and the SED modeling, the total reddening and hence the luminosities were determined. Luminous YSOs and post-AGB stars show similar SEDs and even luminosities and low-resolution spectra are not enough to strictly differentiate between the two ([26],[55]). The final catalogue for the SMC as well as the complete method is published in [26]. From the 66 spectroscopically-verified post-AGB candidates in the SMC, 35 are found to be disc sources. A similar full analysis will be performed for the LMC [27]. A remarkable result is that a significant number of disc objects have luminosities that are consistent with a post-RGB rather than a post-AGB nature [26].

As the full catalogues are still in the making, a global analyses of the chemical diversity is not yet finished. In the next section, we highlight a few results on individual
sources as to illustrate the potentials of the full programme. The follow-up studies concentrate on the interpretation of high-resolution optical spectra we obtained with the UVES spectrograph of the VLT at ESO-Paranal.

4. Individual Sources

4.1. Depletion in LMC Sources

Also in the LMC we found objects which are affected by the depletion process and after discovery of the first source (MACHO 82.8405.15), more followed [15]. We can conclude that also in the LMC depletion seem to be a common process. Like in the Galaxy, the depleted stars show SEDs consistent with discs rather than outflows and some of these objects are RV Tauri pulsators as well. It is interesting to note that objects with disc SEDs cover a wide range of luminosities, from objects likely in a post-RGB state, to quite luminous post-AGB stars ([47],[26]). These objects are probably associated with the late stages of evolution of binaries but to prove this, radial velocity monitoring is badly needed.

4.2. s-Process Elements in the LMC

In Fig.4 we display a spectrum of one of the LMC sources that clearly shows a strong overabundance of s-process elements. The s-process-rich objects we have studied until now in the LMC ([39],[ 46]) are all of low initial mass (around 1.5 \( M_\odot \)) and display metallicities between \(-1.2\) and \(-1.0\), significantly lower than the average in the host galaxy. Despite the large overabundances of s-process elements of around 1.5 to 2 dex, the C/O ratios are modest and are found to be only around 1.5. It is interesting to note that the predicted dependency of the s-process efficiency (a higher \([hs/ls]\) ratio) on the metallicity is not found in the range between \([Fe/H] = 0\) to \(-1.5\).
Figure 4. Spectral comparison between an s-process rich LMC post-AGB star and two Galactic objects with similar spectral types and metallicity. The middle spectrum is also s-process rich, the lower one is not. The very strong Ba line is clear [46].

The 21\,\mu m sources in the LMC [53] were discovered by the SAGE-SPEC collaboration [30] and one of the sources is in common. This object (J052043.86-692341.0) turned out to be post-carbon stars which also displays large overabundances of the s-process elements.

4.3. s-Process Elements in the SMC

Also in the SMC s-process rich post-AGB stars are found [11]. In Fig. 5 we display a spectrum of the very enriched object J004441.04-732136.4. The spectrum of this object is completely swamped by s-process lines (Fig. 5).
Spectral abundance results reveal J004441.04-732136.4 to be one of the most s-process enriched objects found up to date, while the photospheric C/O ratio is only about 2 and a metallicity of [Fe/H] = −1.3. The metallicity is significantly lower than the mean metallicity of the SMC. From the SED, a luminosity of 7600 +/- 200 L_☉ is found. According to evolutionary post-AGB tracks, the initial mass should be about 1.3 M_☉. The photometric variability shows a clear period of 97.6 +/- 0.3 days.

The detected C/O as well as the very high s-process overabundances (e.g. [Y/Fe] = 2.15, [La/Fe] = 2.84) are hard to reconcile with the AGB predictions [11]. The object has a too low C abundance but is remarkably also enriched in O, which is not predicted. The chemical models also predict a high Pb abundance, which is not compatible with the detected spectrum ([10], Fig. 6). A very high $^{12}$C/$^{13}$C is also predicted but this is not yet constrained by observations. We conclude that current AGB models including a 13C-
pocket arising from the third dredge-up, are not able to reproduce the observed low Pb abundances in these objects as well as the enhanced O abundance [10].

Figure 6: Spectrum synthesis around the strongest Pb line of J004441.04-732136.4. The green, red and blue lines give the AGB model prediction abundances of Pb while the black line is the spectrum. The predicted high abundance is clearly not detected. In these highly s-process enriched objects, several lines are not yet identified [11]

5. SUMMARY

The chemical diversity of post-AGB stars in the Galaxy is striking. Only a minority of the objects studied so far shows the results of an efficient AGB nucleosynthesis and dredge-up history. There is a good correlation between chemical enrichment and the presence of the 21µm dust emission feature. A common photospheric anomaly is shown by many objects that are (or likely were) surrounded by a stable long-lived disc: their photospheres show an abundance pattern similar to the gas-phase of the ISM. The refractory elements are depleted while the volatile elements are much less affected.
There is good evidence that the majority (if not all) of these systems are binaries. In the Galaxy, however, the distances of the known post-AGB stars are poorly constrained and hence we launched a research project to study systematically the post-AGB population of both the LMC and SMC. While the research is ongoing we show that quite some interesting objects are already found, illustrating now already that the chemical diversity is also large in the Magellanic Clouds.

We believe that our full systematic survey of the post-AGB population of both the LMC and SMC is needed to understand the chemical diversity also in our Galaxy. This work is ongoing so stay tuned.

REFERENCES


