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# Optically bright post–AGB stars in the LMC:

## an extensive sample study

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**Abstract.** The observational characteristics of the limited Galactic sample of post-AGB stars vary so much that there is no consensus yet on how the detailed studies of individual objects are linked to evolutionary channels. The evaluation is complicated by the fact that the distances, and hence the luminosities, of these objects are poorly known. In this contribution we will report on our project to overcome this problem by focusing on a significant sample of post-AGB stars with known distances: those in the LMC. Via cross-correlation of the infrared SAGE-SPITZER catalogue with optical catalogues we selected a sample of 1500 LMC post-AGB candidates based on their [8]-[24] colour index and estimated luminosity. We determined the fundamental properties of the central stars of 106 of these objects using low resolution optical spectra that we obtained at Siding Spring and at SAAO. Our final catalogue of good candidate post-AGB stars will be presented.

**Key words.** Stars: AGB and post-AGB – Stars: evolution – Galaxies: Magellanic Clouds – Stars: circumstellar matter

## 1. Introduction

Post-AGB stars are evolved stars of intermediate initial mass that have left the asymptotic giant branch (AGB) but did not yet become planetary nebulae (PNe) or cooling white dwarfs. The post-AGB evolution is very fast (Blöcker 1995) and as a consequence not many are known. In the webcatalogue of Torún (Szczerba et al. 2007) only 326 Galactic objects are listed as good candidate post-AGB stars and an additional 107 as possible post-AGB stars.

Based on the shape of their spectral energy distribution (SED), we can split the Galactic post-AGB stars roughly into two distinct classes (see Fig. 2 for some examples). The first subgroup consists of objects with a double-peaked SED of which the peak at higher wavelengths corresponds to the emission of a freely expanding, detached shell of cooling dust and gas. This expanding outflow is the remnant of the heavy AGB mass loss.

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Depending on the strength of the circumstellar reddening, the central star is directly detectable at lower wavelengths. The SEDs of the second type of objects show a broad excess with an onset already in the near infrared, which indicates that there is still hot dust in the system. These SEDs are indicative of a stable disc rather than an expanding envelope (de Ruyter et al. 2006). Although this second class is often overlooked, these objects turned out not to be rare at all in our Galaxy and the objects are associated with binary central stars (e.g. Van Winckel et al. 2009).

The post-AGB evolutionary phase is poorly understood and many questions remain concerning the enormous chemical and geometrical diversity we observe (e.g. Van Winckel 2003; Siódmiak et al. 2008; Verhoelst et al. 2009; Ueta et al. 2007, and references therein) and how all individual studies of post-AGB stars are connected by evolutionary channels. One of the reasons is that for most objects the distance and hence the intrinsic luminosity are largely unknown. In these proceedings, we report on our project to overcome these problems by looking at a large sample of post-AGB stars with a known distance: those in the LMC.

## 2. Sample selection

### 2.1. SAGE data products

The Spitzer surveying the agents of a galaxy's evolution (SAGE) project (Werner et al. 2004) mapped a $7^\circ \times 7^\circ$ region of the LMC using the IRAC camera at wavelengths of 3.6, 4.5, 5.8 and 8.0 $\mu$m and the MIPS camera at 24, 70 and 160 $\mu$m. The survey was performed over two epochs in 2005 and details can be found in Meixner et al. (2006). In total, over 6.9 million sources were detected with IRAC and about 40 000 with MIPS. We made use of the SAGE second release data products (September 2009) combining both epochs of the survey. The Spitzer IRAC sources are bandmerged with the Two Micron All Sky Survey (2MASS) in filters $J$, $H$ and $K_s$ (1.24, 1.66, and 2.16 $\mu$m) (Skrutskie et al. 2006) and can be found at the websites of the Spitzer Science Center (SSC) and NASA/IPAC.

### 2.2. Colour criteria

To come to a selection of post-AGB candidate stars we adopted the following strategy. First we selected all sources with a valid 8 $\mu$m detection in the IRAC archive catalogue, we cross-correlated the epoch 1 and epoch 2 MIPS 24$\mu$m catalogues and retained only those objects which were detected within 3" in either epoch. When multiple matches were found we only retained the closest one. At this stage we still had 25 194 sources.

Next, we narrowed our sample down through a colour selection inspired by what is known from Galactic post-AGB sources. It turns out that the known Galactic disc sources (de Ruyter et al. 2006) all obey $F(24) > 0.4 \times F(8)$ or [8]-[24] > 1.384 when folded on the Spitzer filters, so we impose the same criterion on our sample of post-AGB candidates. This way we select both outflow sources, which have typically colder dust with $F(24) > F(8)$, and disc sources. This criterion is deliberately meant not to be very restrictive: it is only intended to select an initial sample of post-AGB candidates which will be refined in the next steps. 16 570 objects in the SAGE catalogue live up to this standard.

We subsequently correlated the sample with three optical catalogues using a search radius of 1" from the IRAC position, and only retaining the objects for which an optical magnitude in the U, B, V, R or I-filter was listed. We found that Massey's catalogue of the UBVR CCD survey of the Magellanic Clouds (Massey 2002) brought forth 489 matches, correlation with the Guide Star catalogue Version 2.3.2 (GSC2.3) (STScI, 2006) (Spagna et al. 2006) resulted in 1659 common objects and the LMC stellar catalogue of Zaritsky et al. (2004) contained 5025 mutual sources of which 4985 were original for this catalogue and not coming from Massey's. After removal of all objects without optical data our total sample contains 5613 stars.

### 2.3. Luminosity cut

So far, all objects with infrared excesses fulfilling the colour criteria are selected. Obvious

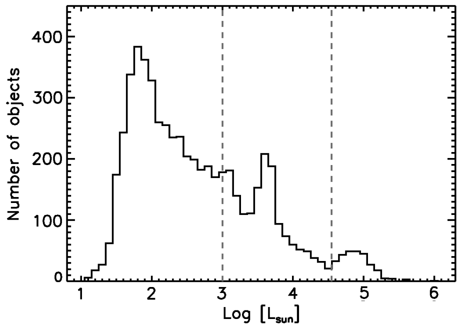


**Fig. 1.** Histogram of the roughly calculated luminosities of all objects in our sample before the luminosity cut. The dashed gray lines indicate a lower and upper limit for the luminosity of post-AGB stars and are located at 1000 and 35 000 $L_{\odot}$ respectively.

candidate intruders in the sample are supergiants and young stellar objects (YSOs). To refine our selection further we therefore impose a luminosity criterion. As we have no information on the spectral types of the different central objects, we simply integrate all flux in the system by fitting up to 3 black bodies (BB) to all available photometry without applying dereddening. To compute the luminosity, we make use of a distance modulus of 18.49 (e.g., Clement et al. 2008). The integral of the BB fit is a rough approximation of the true luminosity, as it implies spherical symmetry and the absence of ISM redenning. A histogram of the results can be seen in Figure 1.

The calculated luminosities display three clearly distinct peaks of which the luminosity values of the middle one agree with what we expect for post-AGB stars (Blöcker 1995). The peak at lower values corresponds to luminosities typical of rather massive YSOs and we remove the bulk of them from the sample by introducing a luminosity cut at 1000 $L_{\odot}$. This is not a strict condition so we may expect that some luminous YSOs are still present in our sample. The third peak at the highest luminosities corresponds to supergiants which we dispose of by using a luminosity cut at 35 000$L_{\odot}$. This agrees with a $\log(L/L_{\odot})$ of about 4.5 and is hence an upper limit for the luminosity of a 7 $M_{\odot}$ post-AGB star as has been computed by Blöcker (1995), taking into account that the values we compute tend to overestimate the true luminosity. After rejection of the objects whose estimated luminosity does not fall within the predicted range for post-AGB stars, our sample still contains 1518 objects.

### 2.4. MIPS 70 and 160 $\mu$m data

A cross correlation with the MIPS 70 and 160 $\mu$m catalogues, SAGELMCfullMIPS70 and SAGELMCfullMIPS160, with a search radius of 3” reveals that 226 objects in our sample have a detection at 70 $\mu$m of which one is also listed in the 160 $\mu$m catalogue. With these extra datapoints, it can be seen that the SED of 7 of these sources is monotonically increasing towards wavelengths redder than 70 $\mu$m which suggests that the bulk of the energy is radiated beyond this point. This is typically not observed in Galactic post-AGB stars, regardless of whether it has an SED indicative of disc or an outflow. We suspect these objects to be galaxies or embedded, massive YSOs, rather than post-AGB stars. After their removal, our final sample contains 1511 post-AGB candidates.

### 2.5. Subtypes

To get an idea of the amount of objects with a disc and those with a freely expanding, detached shell in our final sample we introduce an upperlimit of $F(24) < 3 \times F(8)$ for the flux at 24 $\mu$m for the former. This implies that the star emits more flux at 8 $\mu$m than it does at 24 $\mu$m and hence the dust will be closer to the photosphere of the central star. We find that according to this extra cut 625 objects have a circumstellar disc, 536 have a freely expanding, detached shell and 350 objects fall in the gray zone in between where $F(8) < F(24) < 3F(8)$ and no conclusion on their stellar environment can be made.

## 3. Low resolution optical spectra

The colour and luminosity criteria we used are not very restrictive, so obviously not only post-AGB stars will occupy the sample. Similar colours can be detected from, amongst others, background galaxies, compact HII regions, PNe, luminous YSOs and some remaining supergiants, as well as foreground stars. We obtained low resolution spectra to eliminate such unwanted objects and to make an initial study of those which appear to be post-AGB stars. So far, we obtained spectra for 106 of the brightest objects in our sample with the ANU 2.3 m telescope at the Siding Spring Observatory in Australia and the SAAO 1.9 m Radcliffe telescope. All spectra were classified on the MK system, using the published spectra of Jacoby et al. (1984) as templates. For the objects observed at SAAO, we had a personal library of standard stars that were observed with the same instrumentation.

Of the 106 observed objects in our final sample, only 9 are rejected because they clearly cannot be post-AGB stars. We identified 7 galaxies and 2 PN-like objects. The low resolution, optical spectra we took of the remaining 97 objects conform to what we expect from post-AGB sources. We detect all spectral types from late O to mid M, with number density peaks at B, F and K. For 14 objects, however, some puzzling features in the spectra prevent us from determining the correct spectral type. We notice three carbon stars and also observe that 23 objects display emission lines.

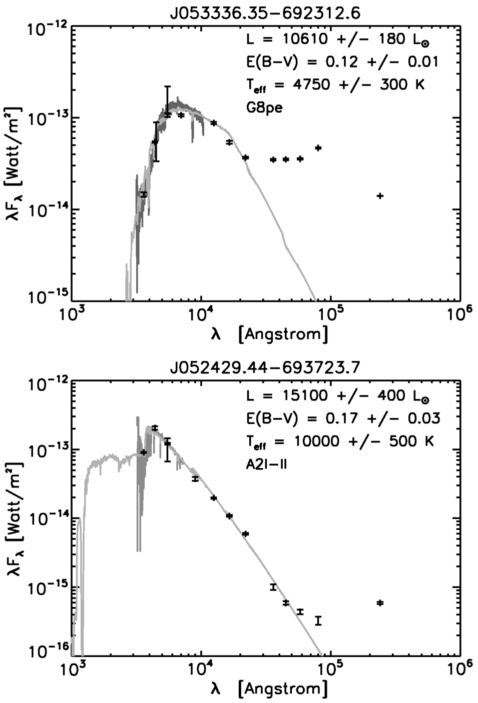


**Fig. 2.** Example SEDs of post-AGB candidates with a circumstellar disc (top panel) and a freely expanding, detached shell (bottom panel).

## 4. Analysis of the sample

### 4.1. Spectral energy distributions

To estimate the total reddening as well as to determine the luminosity of the objects with an optical spectrum more accurately, we developed a method based on a Monte Carlo simulation to minimise simultaneously for the effective temperature as well as for the total reddening of the star. For each object, we allowed a small range in temperatures based on the spectral type we deduced from the spectrum. We only use one model for each temperature since our spectra are not accurate enough to determine $\log g$. A lower limit of 0.04 is imposed for E(B-V) to account for Galactic interstellar extinction towards the LMC. For the minimisation itself, the photometry up to 25 000 Å was used. This limit is a compromise between retaining enough datapoints for the minimisation procedure and the fact that at wavelengths longer than 13 000 Å the thermal radiation of the circumstellar material may already dominate in the case of objects with a circumstellar disc. Because of the large uncertainty on the flux level, the spectra itself were left out of this minimisation process. Also, the data from the Guide Star Catalogue were excluded from the procedure if other photometric data were available, because of their larger errors and sometimes significant difference from magnitudes found in the other two optical catalogues. To get an estimation of the errors on the different parameters, we performed a Monte Carlo simulation with 250 steps. The final luminosities are calculated by integrating the appropriate stellar model that fits the dereddened optical photometry using a distance modulus of 18.49.

The results of this minimisation procedure are very good in general, except for objects with spectral types O and B because we lack photometry at wavelengths below 3 600 Å where a significant part of the luminosity is radiated. Most parameters are rather stable, but unfortunately the luminosity and reddening are strongly dependent on the atmosphere model. Some example SEDs can be found in Figure 2.

A small adaptation of this procedure, namely allowing the entire range of temperatures in the minimisation procedure, allows us to broaden this method to objects without a spectrum. A small test on the objects of which the spectral type is known reveals that for the bulk of the objects the results are rather reliable. The temperature is restricted the best, followed by the value of E(B-V). The computed value of the luminosity remains the most uncertain, by its great dependence on the other two parameters. If there are enough data to describe the photosphere well, we prefer the new value since it is a more realistic approximation. However for some objects, the new procedure renders less good results: the lack of data at wavelengths below 3 600 Å implies that the luminosity of hot stars will be overestimated and because the SED method does not deal appropriately with high values of E(B-V), no good values will result for heavily obscured sources. Hence we discard those luminosities and retain the value calculated in section 2.3 instead.

### 4.2. Luminosity distribution

In Fig. 3 we show the histogram of all final luminosities while distinguishing between the different subtypes. When we look at the entire sample, we see that there is a peak from a few hundreds to a few thousands solar luminosities which are the expected values for a post-AGB star. There is a bias towards lower luminosities and hence masses as is expected from their slower evolution. The slow monotonous drop towards high luminosities reveals that the upper luminosity cut probably succeeded in removing all supergiants from the sample. A smaller second peak towards the lower luminosities remains, indicating that some YSOs are likely still present.

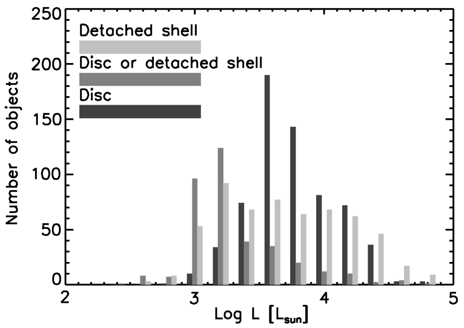


**Fig. 3.** Histogram of the luminosity distributions of the different subsamples.

Both sources with an SED indicative of a disc as those with a freely expanding, detached shell span the entire range of luminosities, but the distinction between both types seems to be clearer at higher values of the luminosity. The objects with an expanding shell are distributed almost evenly over all luminosities with possibly a small peak near the lower values while the sources with a circumstellar disc show a clear peak in the middle of their distribution.

## 5. Evaluation

To evaluate our selection procedure, we cross correlate the sample of post-AGB candidates after every step in this procedure with empirical catalogues of AGB stars (van Loon et al. 1999), PNe (Reid & Parker 2006) and the galaxies listed on the NASA/IPAC Extragalactic Database (NED)[1] and colour and/or magnitude based catalogues of YSOs (Whitney et al. 2008) and red supergiants (Oestreicher et al. 1997). It turns out that our initial criterion to lose all data with [8.0] − [24] > 1.384 already removes some galaxies, red supergiants and AGB stars from the sample, but many other types of objects still remain. The luminosity cut we performed to

[1] The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

get rid of the bulk of the supergiants and YSOs, was indeed effective. The upper limit removes all remaining supergiants and some extra galaxies and AGB stars while the lower limit makes sure a lot of YSOs, PNe and galaxies are also left out of the sample. A rather small amount of objects are listed in the MIPS 70 and an even smaller number in the $160\,\mu$m catalogue. Only for the YSOs, PNe and galaxies, the amount of objects listed in these catalogues is big enough to draw some conclusions. It turns out that the requirement of not having a monotonically increasing SED mainly removes YSOs and especially those that are listed with a high probability from the sample. About 10% of the PNe are also discarded. Although a lot of galaxies have MIPS 70 and $160\,\mu$m data, almost none of them display an SED of this shape.

When we have a closer look at the pollution of the lists of the different post-AGB subtypes, it can be seen that the subsample of objects with a circumstellar disc is mainly polluted by AGB stars while the objects with a freely expanding, detached shell overlap more in colour with YSOs and PNe. The intermediate subclass possibly contains all these kinds of objects.

## 6. Conclusions and future prospects

We constructed a catalogue of 97 high probability and 1405 candidate post-AGB stars while only about 25 were previously known in the LMC. However, spectra remain necessary to confirm the object is indeed a post-AGB star as many other types of object display similar colours.

The luminosities we computed remain rather uncertain because they are sensitive to changes of the atmosphere model, the value of E(B-V) and the applicability of the ISM reddening law for circumstellar reddening. As in the Galaxy, also in the LMC post-AGB sources with a circumstellar disc are frequent. A paper on these results is being written.

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