STELLAR EVOLUTION IN THE POST-AGB STAGE

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Abstract: We present the catalogue resulting of 15 years of spectroscopic observations of a sample of 254 IRAS sources showing far infrared colours similar to those of well-known planetary nebulae. 106 sources are classified as post-AGB stars, 21 as "transition sources", and 36 as planetary nebulae, some of them strongly reddened. The large majority remained unidentified in the literature or were poorly known by the time when this spectroscopic survey started. Among the rest of sources in the sample, we were also able to identify 38 young stellar objects, 5 peculiar stars and 2 Seyfert galaxies. Up to 46 sources in our spectroscopic sample were found to show no optical counterpart, most of them are suggested to be heavily obscured post-AGB stars, rapidly evolving in their way to become planetary nebulae. A preliminary analysis of the distribution of post-AGB stars and PN in the IRAS two-colour diagram is presented. We also analyse the spectral type distribution of the post-AGB stars observed.

1 Introduction

Post-Asymptotic Giant Branch (post-AGB, hereafter) stars are rapidly evolving low- and intermediate-mass stars in the transition phase from the AGB to the Planetary Nebula (PN, hereafter) stage [1, 2, 3]. AGB stars are pulsating stars, very bright in the infrared, but they can become heavily obscured in the optical by thick circumstellar envelopes formed as a consequence of their strong mass loss (up to 10^{-4}M$_\odot$/yr). When the mass loss stops the AGB star enters the post-AGB stage, which is also accompanied by the cessation of the stellar pulsations. This is followed by a decrease in the optical depth of the circumstellar envelope as a consequence of the expansion, which implies that the central star can be seen again in the optical range if it was ever obscured at the end of the AGB. During this process, the effective temperature of the central star increases. This leads to a rapid change in its spectral type, which migrates from late to early in timescales of a few thousand years [4].

The terminology used to define the various stages preceding the formation of a PN is sometimes confusing. In this work the term 'post-AGB star' will be applied to those sources which have already ended the strong mass-losing AGB phase. When the temperature of the central star is hot enough (T$\geq$20 000K), the ionization of the envelope starts and we consider the star enters the PN stage. We will use the term 'transition sources' for the stars in an intermediate stage between post-AGB and PN, whose spectra are characterized by the simultaneous detection of stellar continuum and shock-excited emission lines.

The initial goal of the observations made was the discovery of new PN among the 1084 sources included in the so-called 'GLMP catalogue' [5]. This was a colour-selected sample of IRAS sources showing the characteristic far-infrared colours of well known PN. The strategy was based on the fact that PN are located in a well defined region of the IRAS two-colour diagram [12]−[25] *vs* [25]−[60] almost exclusively populated by PN and post-AGB stars. In this region, only a small overlap exists with some young stellar objects and a few Seyfert galaxies, while normal stars and galaxies show completely different far-infrared colours [6]. Not unexpectedly, as a byproduct of our search for PN, we found that many of the observed stars were actually post-AGB stars and transition sources.

The use of IRAS data has proved to be a highly successful method to identify new candidate sources in the transition from the AGB to the PN stage. Their strong infrared excess makes them very bright in the infrared and easily detectable at these wavelengths. Based on their characteristic colours, potential candidates were compiled in the past by [8, 9, 10, 6, 11] and other authors, and reported in the Strasbourg-ESO catalogue of galactic PN, SECGPN [12]. More specific searches were also made for planetary nebulae (PN) [13, 14] or for post-AGB stars with optically bright counterparts [15, 16] in the last fifteen years. Unfortunately, in many cases no spectroscopic confirmation is provided in the literature about the nature of the newly discovered sources. One of the main reasons for this is the poor astrometric accuracy of the IRAS data (~15-30 arcsec), which makes the identification of the optical counterparts of the selected IRAS sources very difficult, especially in crowded fields close to the galactic plane and/or in the direction of the galactic centre.

In this work we present the results of an optical survey of stars candidates to be in the post-AGB or PN stage, selected by their IRAS colours, for which we have obtained optical spectra. In this way we provide information about the envelope (by means of the IR colours) and about the central star (by means of its optical classification). An extended version of this paper can be found in [17].

2 Selection criteria

The selection criteria applied in this work are adapted from those proposed by [6].

(i) The source must be well detected at 12, 25 and 60 μm in the IRAS PSC [7]. The required flux quality for each band is: FQUAL (12 μm) $\geq$ 2; FQUAL (25 μm) = 3; FQUAL (60 μm) = 3.

(ii) The required ratios between the IRAS photometric fluxes are the following:

$$\frac{F_\nu\ (12\ \mu\mathrm{m})}{F_\nu\ (25\ \mu\mathrm{m})} \leq 0.50;$$

$$\frac{F_\nu\ (25\ \mu\mathrm{m})}{F_\nu\ (60\ \mu\mathrm{m})} \geq 0.35.$$

(iii) When data at 100 μm are of good quality (FQUAL (100 μm) = 3), we further impose:

$$\frac{F_\nu\ (60\ \mu\mathrm{m})}{F_\nu\ (100\ \mu\mathrm{m})} \geq 0.60.$$

(iv) Low IRAS variability index (VAR $\leq$ 60 %).

The choice of the criteria (i), (ii) and (iii) is mainly a consequence of the range of dust temperatures (T_d) expected in the circumstellar shells of post-AGB stars. If we assume a typical luminosity for a post-AGB star of L=$10^4 L_\odot$, following [18], the dust temperature in the shell would be:

$$T_\mathrm{d} = 1.658\, f^{-1/5} r^{2/5} L_*^{1/5} \tag{1}$$

where f is the value of the emissivity of the dust grains at 50μm, r is the radius of the shell in pc and L_* is the luminosity of the central star in solar units.

Using $f(50\,\mu\mathrm{m}) = 0.004$ [19], we find a T_{d} between 200 K and 80 K for r between 0.01 pc and 0.1 pc, respectively (the expected range of radii of the expanding circumstellar envelope).

The low IRAS variability is imposed to exclude AGB stars from the sample, since they are known to be strongly variable stars.

3 Observations

The spectroscopic observations were conducted during several runs spanning 15 years from March 1988 to June 2003. The observations from the Southern Hemisphere were carried out in most cases using the 1.5 m ESO telescope at the European Southern Observatory (La Silla, Chile), equipped with a Boller & Chivens spectrograph. The first and last run of observations were carried out at the 3.6 m ESO telescope, located at the same site, using the ESO Faint Object Spectrograph and Camera EFOSC1 in the first run and EFOSC2 in the last. The observations from the Northern Hemisphere were carried out using the 2.5m Isaac Newton Telescope at the Observatorio de El Roque de los Muchachos (La Palma, Spain), with the IDS spectrograph, and the 2.2 m telescope at the Observatorio Hispano-Alemán (Calar Alto, Spain), also equipped with a Boller & Chivens spectrograph.

4 Results

4.1 Composition of the sample

A total of 254 different IRAS fields were searched, resulting in the successful identification of 208 optical counterparts believed to be associated with the corresponding IRAS sources.

According to our analysis, 106 sources in our sample can be identified as post-AGB stars with optical counterpart, 21 as sources in the transition phase between post-AGB and PN (transition sources, hereafter), and 36 as PN. There are 46 objects for which we did not find any optical counterpart to the IRAS sources, most of which are believed to be obscured post-AGB stars. The sources in the sample not related with the post-AGB evolutionary stage are two Seyfert galaxies, a few peculiar sources, and 38 sources identified as young stellar objects. In this group we have included T-Tauri stars, Herbig Ae/Be stars, Herbig-Haro objects, Vega-like stars and compact HII regions. The complete list of objects as well as their optical spectra, identification charts and astrometric coordinates can be found in [17].

A first analysis of the obtained results suggests that the adopted selection criteria turned out to be very efficient in the detection of evolved stars among the IRAS sources included in our spectroscopic survey, as it was originally intended. Only 38 of the sources observed (∼17%) are identified as young stellar objects, and 2 as galaxies (less than 1%).

In contrast, up to 209 sources, representing 81% of the sample, are found to be associated with the short transition phase between the end of the AGB phase and the formation of a PN. Among them, the majority of these sources are considered to be post-AGB stars (106 with an optical counterpart, plus possibly 46 more, heavily obscured ones) or 'transition sources' (21). For many of them there was no previous spectroscopic information, as is clearly reflected by the fact that only 24 of them have a spectral type association in the SIMBAD database.

The PN detected in our survey are in many cases far from typical, since we have excluded from the sample those that were very well-known. Many of them are of very low excitation, young and compact, and sometimes strongly reddened, which may be the reason why they escaped detection in classical optical surveys made in the past, usually based on the identification of sources strongly emitting in the characteristic [O III] nebular emission line.

4.2 Spectral classification

We have carried out a spectral classification in the MK system of all the observed sources showing stellar continuum. It was performed taking the spectral type libraries included in several catalogues [20, 21, 22] as references, and assuming luminosity class I by default (expected because of the low gravity of stars in the post-AGB phase).

The excitation classes for the PN have been defined according to the ratios of the intensities of nebular lines to Hβ. They are an indirect measure of the central star temperature. We have used the classification proposed by [23] and [24].

We have found post-AGB stars belonging to all spectral types from M to B shown in Figure 1, in what can be interpreted as an evolutionary sequence towards higher effective temperatures on their way to become PN. If this interpretation is correct, the distribution of spectral types should be a good indicator of the time spent by these stars in each range of temperatures. The same analysis could be applied to high mass stars, but in this case, part of the evolution would take place while the central star is still heavily obscured by the circumstellar envelope, and by the time it could be observed in the optical, it would have already evolved significantly towards hotter temperatures.

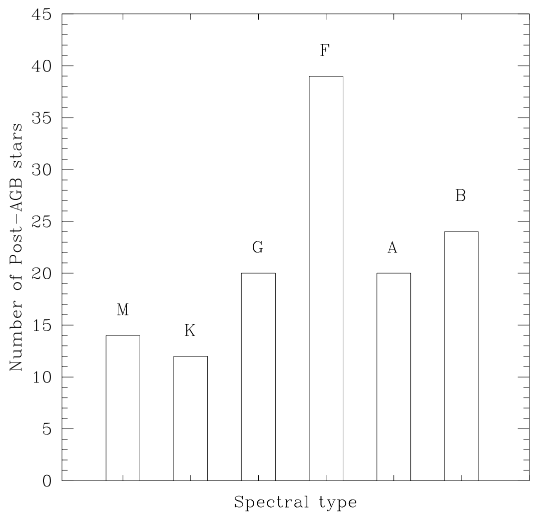

Figure 1: Relative distribution of spectral types for the post-AGB stars in our sample. See text for details.

We find that the distribution of spectral types in our sample of post-AGB stars and transition objects, not considering M and K spectral types, is not compatible with any of the three theoretical models used by [25] with a 95% confidence level. We suggest this can be due to the fact that our sample is a combination of objects with different core masses, as it is expected from the selection criteria chosen, which do not favour any particular core mass range.

4.3 Distribution of the sample in the IRAS colour-colour diagram

In Figure 2 we show the IRAS colour-colour diagram of all the sources included in our spectroscopic survey, where special symbols are used to distinguish between the different types of objects: PN, post-AGB stars, galaxies, young stellar objects

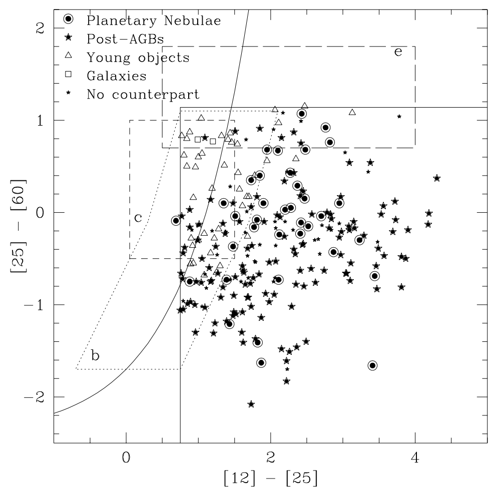

Figure 2: IRAS colour-colour diagram with the location of all the objects included in our spectroscopic survey. See text for details.

and objects observed for which no counterpart was found (transition sources have been included with post-AGB stars).

The boxes with dashed boundary lines indicate areas mostly populated by variable OH/IR stars (box *b*, dotted line), T-Tauri and Herbig Ae/Be stars (box *c*, short dash) and compact HII regions (box *e*, long dash) [26] and references therein. We have maintained the labels used in that paper.

The two solid straight lines -vertical and horizontal- show the limits of the area defined by our selection criteria. The solid curve has been modeled by [27], and shows the location of O-rich stars as they evolve along the AGB from M-type Miras to variable OH/IR stars.

In Figure 2 we can analyse the distribution of the different classes of sources in our sample in this diagram. PN and post-AGB stars are spread almost regularly over the diagram. It is important to remark that there is a high probability ($>$ 95%) of finding a post-AGB or a PN in the region that does not overlap with regions *b*, *c*, or *e*.

It is also easy to recognise the position of the young stellar objects, marked with open triangles. Almost all of them are located, as expected, either in box *c* or *e*.

5 Conclusions

We have presented the results of an extensive spectroscopic survey on a sample of 254 IRAS sources showing infrared colour characteristics of PN. The selection criteria used turned out to be very efficient in discovering new post-AGB stars and transition sources evolving from the AGB to the PN stage, resulting in the identification of 152 post-AGB stars (46 of them candidates to be post-AGB stars without an optical counterpart), 21 transition sources and 36 PN. This constitutes the largest catalogue of post-AGB stars built up so far.

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