Supergiants transiting towards white dwarfs

Valentina G. Klochkova,

Special Astrophysical Observatory RAS, Nizhnij Arkhyz, Karachai-Cherkessia, Russia; email: valenta@sao.ru

Abstract. Observational manifestations of far evolved stars at the asymptotic giants branch and their nearest descendants are briefly considered. Main results of their chemical composition determinations based on long term high resolution spectroscopy at the 6-m telescope are also briefly summed up. A new kind of peculiarity of optical spectra is found and discussed: splitting or asymmetry of strongest absorptions in the optical spectra of selected post-AGB stars with envelopes and atmospheres enriched in carbon and s-process heavy metals.

1. Introduction

Asymptotic giants branch (AGB) and post-AGB stars are the principal suppliers of heavy metals and important suppliers of carbon and nitrogen to the interstellar medium. It is currently believed that about half of metals heavier than iron are synthesized in the s-process in deep layers of AGB–stars with initial masses $\lesssim 3 \div 4 M_\odot$. Newly synthesized nuclei are moved to surface levels of the star by mixing (the so-called third mixing, TDU) and, under the influence of the stellar wind, into the circumstellar medium. A detailed description of these processes and additional references can be found in reviews by Herwig (2005) and Käppeler et al. (2011). By supplying heavy metals and carbon to the interstellar medium, AGB stars participate in the chemical evolution of their galaxies as a whole. However, although observations have enabled the identification of numerous evolved stars with carbon-enriched envelopes, the ejection of heavy metals into the circumstellar medium has not been directly detected.

On the Hertzsprung–Russell diagram stars with initial mass approximately $2 \div 8 M_\odot$ undergoing the short-lived protoplanetary nebulae (PPN) stage evolve from the AGB toward the planetary nebula (PN) stage at almost constant luminosity, getting increasingly hotter in the process. These descendants of AGB stars are low-mass cores with typical masses of $0.6 M_\odot$ surrounded by an extended and often structured gaseous envelope, which formed as a result of substantial mass loss by the star during the preceding evolutionary stages. The internal structure of an AGB–star is very specific. A degenerate C/O core is surrounded by thin helium and hydrogen shells nuclear processing in which become in turn active. Thus final phase of AGB evolution is characterized by recurrent thermal pulses in helium shell. Each thermal pulse causes an increase in convection and dredge-up of fresh synthesized carbon and heavy metals to surface stellar layers. In the case of more massive stars with initial masses $3 \div 8 M_\odot$ hot-bottom burn-
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ing (HBB) provides a synthesis of lower-mass chemical elements from Ne to Si (Herwig (2005)).

2. Observational data and main results

We have carried out numerous spectroscopic observations of supergiants with IR excesses using the 6-m telescope of the Special Astrophysical Observatory over the past two decades. The initial aim of the program was to determine the fundamental parameters of the program stars and to study chemical abundance anomalies in their atmospheres. The combined information we have obtained can be used to reliably identify a star evolutionary stage. In the course of this program, we recognized the need for additional studies aimed at identifying spectral peculiarities and time variations of the spectral features. Studies of the velocity fields in the atmospheres and envelopes of the program stars were also required.

Spectral data were mainly obtained at the Nasmyth focus of the 6-meter telescope with the NES spectrograph developed by Panchuk et al. (2009) using a 2048×2048-pixel or 2048×4096-pixel CCD chip and an image slicer, providing a spectroscopic resolving power of $R = 60,000$ within a wide wavelength range to be observed simultaneously. The spectra of faint stars (the optical counterparts of the IR sources IRAS 04296+3429 and 20000+3239) were obtained with the PFES echelle spectrograph designed by Panchuk et al. (1998) at the primary focus of the 6-m telescope. With a $1024\times1024$-pixel CCD chip, this spectrograph provides a resolving power of $R = 15,000$. Details of our spectrophotometric and position measurements of the spectra are described by Klochkova (2014).

The primary conclusion of the analysis of the properties of the supergiants with infrared excess studied so far is that the available sample of these objects is inhomogeneous (Klochkova 2014). These objects are found to exhibit a great variety of peculiarities in the optical spectra of their central stars, the chemical composition of their atmospheres and envelopes, and the morphology and kinematic state of their circumstellar envelopes. We should point out, in particular, that supergiants with infrared excess include RV Tau type variables. These variable stars with near-infrared excesses undergo the post–AGB evolutionary stage, and, as it was shown by van Winckel (2007), most of them are binaries.

Besides some stars of the program were identified as belonging to massive stars far evolved. Most known objects with unclear status are high luminous stars V1302 Aql (= IRC+10420) and HD 179821 (= IRAS 19114+0002). Their properties (high luminosity, spectral peculiarities, presence of circumstellar envelopes) are similar to that observing for PPN. But thanks to the reinforced research during last decades (see Klochkova et al. (1997); Humphreys et al. (2002); Klochkova et al. (2016); Sahin et al. (2016) and numerous references therein) both stars are now considered to be the most unambiguous massive stars with a highest mass loss rate which undergoes a short-term evolutionary transition from a red supergiant to a Wolf-Rayet star. Predecessors of the yellow hypergiants are massive (initial mass $\geq 20 \, M_\odot$) and the most luminous stars, which lose a significant part of their mass after leaving main-sequence, become red supergiants, and later proceed to yellow supergiants.

Quite opposite conclusions were obtained for the star BD$-6^\circ1178$ which was considered to be a candidate to PPN according to the observed excess of radiation
Table 1. Characteristics of circumstellar envelopes of the IR sources identified with the program post-AGB stars. The morphological type of the circumstellar envelope is given in accordance with Ueta et al. (1998); Sahai et al. (2007); Siodmiak et al. (2008); Lagadec et al. (2011). The velocity $V_{\text{exp}}$ was determined from the positions of CO and C$_2$ bands and the circumstellar components of the Ba ii lines. The appearance of the C$_2$ Swan bands (emission or absorption) is indicated in parantheses in the fourth column.

| IR source star | Envelope morphology | $V_{\text{exp}}$, km/s | CO | C$_2$ | Ba ii |
|----------------|---------------------|-------------------------|----|-------|-------|
| IRAS 04296+3429 | bipolar + halo + bar | 10.8$^4$ | 7.7 (abs)$^6$ | 12 (emis)$^7$ |
| CGCS 6080     |                     |                        |    |       |       |
| IRAS 07134+1005 | elongated halo      | 10.2$^1$ | 8.3 (abs)$^9$ | 11 (emis)$^8$ |
| CY CMi        |                     |                        |    |       |       |
| IRAS 08005−2356 | bipolar            | 100;2$^2$ | 43.7 (abs)$^6$ | 42 (abs)$^9$ |
| V510 Pup      |                     |                        |    |       |       |
| IRAS 19500−1709 | bipolar            | 17.2, 29.5$^4$ | 10, 30–40$^3$ | no | 20 & 30$^{10}$ |
| V5112 Sgr     |                     |                        |    |       |       |
| IRAS 20000+3239 | elongated halo     | 12.0$^4$ | 12.8 (abs)$^6$ | 11.1 (abs)$^{11}$ |
| CGCS 0857     |                     |                        |    |       |       |
| RAFGL 2688    | multipolar + halo + arcs | 17.9, 19.7$^5$ | 17.3 (abs)$^9$ | 60 (emis)$^{12}$ |
| V1610 Cyg     |                     |                        |    |       |       |
| IRAS 22223+4327 | halo + lobes       | 14–15$^5$ | 15.0 (abs)$^6$ | 15.2 (emis)$^{13}$ |
| V448 Lac      |                     |                        |    |       |       |
| IRAS 22272+5435 | elongated halo + arcs | 9.1–9.2$^1$ | 9.1 (abs)$^6$ | 10.8 (abs)$^{14}$ | 10$^{15}$ |
| V354 Lac      |                     |                        |    |       |       |
| IRAS 23304+6147 | quadrupole + halo + arcs | 9.2–10.3$^3$ | 13.9 (abs)$^6$ | 15.5 (emis)$^{16}$ | 15.1$^{16}$ |
| CGCS 6918     |                     |                        |    |       |       |

References: 1 – (Hrivnak & Bieging 2005), 2 – (Hu et al. 1994), 3 – (Bujarrabal et al. 1992), 4 – (Omont et al. 2002), 5 – (Loup et al. 1993), 6 – (Bakker et al. 1997), 7 – (Klochkova et al. 1999), 8 – (Klochkova et al. 2007), 9 – (Klochkova & Chentsov 2004), 10 – (Klochkova 2013), 11 – (Klochkova & Kipper 2006), 12 – (Klochkova et al. 2009b), 13 – (Klochkova et al. 2010), 14 – (Klochkova et al. 2009), 15 – (Klochkova 2009), 16 – (Klochkova et al. 2015).

in the 12–60 $\mu$m wavelength region and its position on the IR colour–colour diagram. But Klochkova & Chentsov (2008) based on the high-resolution spectra are shown for the first time that BD−6°1178 is a spectroscopic binary (SB 2). Their components have close spectral types and luminosity classes: F5 IV–III and F3 V. The classification of BD−6°1178 as a supergiant in the transition stage of becoming a planetary nebula does not confirm. BD−6°1178 probably is a young pre-MS stars. Moreover it is possibly a member of the 1c subgroup of the Ori OB1 association.

The next important results of our study is the formation of a small homogeneous subsample of PPNe whose atmospheres are enriched in carbon and heavy metals synthesized during the AGB evolution. All these objects are listed in Table 1. Their IR spectra contain an unidentified emission feature at 21 $\mu$m (Hrivnak
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et al. 2009; Kwok et al. 1999) which arises in the circumstellar medium. The large excesses of carbon and heavy metals in the atmospheres of these post-AGB stars in Table 1 were found for the central stars of IRAS04296+3429 (Klochkova et al. 1999), 07134+1005 (Klochkova 1995), 23304+6147 (Klochkova et al. 2000a); 20000+3239 (Klochkova & Kipper 2006); RAFGL 2688 (Klochkova et al. 2000b); and for IRAS 22272+5435 (Klochkova et al. 2009; Klochkova 2009). The chemical abundances for five of the stars from Table 1 were also determined by van Winckel & Reyniers (2007).

In addition to objects with carbon-enriched atmospheres, Table 1 also contains the poorly studied IR source IRAS 08005−2356. Data on the atmospheric elemental abundances of its central star or the presence of the 21 µ band in its IR spectrum are not available. However, Klochkova & Chentsov (2004) consider IRAS 08005−2356 to be related to the other sources in Table 1, because its optical spectrum contains Swan bands of C\textsubscript{2} and emissions of neutral hydrogen, with some metal lines displaying emission–absorption profiles, and its circumstellar envelope was detected by Hu et al. (1994) in CO emission. Thus, we may suspect that IRAS 08005−2356 a full member of this small sample.

We tried to consider additional manifestations of circumstellar envelopes in the optical spectra of post-AGB stars, concentrating on an analysis of this uniform sample of stars whose atmospheric chemical abundances have been shown in earlier former studies to have changed in the course of their evolution. Attempts to find an interconnection between the morphology of the envelope and the peculiarities of the chemical composition of the central star revealed no strict correlation. It may nevertheless be concluded that objects with enriched atmospheres (IRAS 02229+6208, 04296+3429, 19500−1709, and 23304+6147) mostly have structured (bipolar, quadrupole, etc) envelopes. However, objects with enriched atmospheres also include IRAS 05113+1347, whose envelope even the HST failed to resolve, as well as IRAS 05341+0852 and 07134+1005 with envelopes in the form of elongated haloes.

One should also pay attention to IRAS 19475+3119, which has a structured envelope, whereas the atmosphere of its central star HD 331319 is not enriched in either carbon or heavy metals. However, strong helium lines were found by Klochkova et al. (2002) in the spectrum of HD 331319. The presence of these lines in the spectrum of a star with $T_{\text{eff}} = 7200$K results in a significant helium over-abundance was detected by Klochkova et al. (2002) in its atmosphere. It should be mentioned here about detection of large lithium and sodium overabundance for the star V2324 Cyg (= IRAS 20572+4919) (see more details Klochkova et al. (2008)). Results for these two stars permit us to propose that their initial mass was more than 3$M_{\odot}$ and HBB and dredge-up were effective at their AGB stage.

3. Detection of a new type of peculiarities in the optical spectra of post-AGB stars

Further, we concentrate on new properties of the optical spectra of a small subsample of post-AGB stars, from the Table 1 whose circumstellar envelopes of these stars have complex morphologies, and are also enriched in carbon, manifest in the presence of C\textsubscript{2}, C\textsubscript{3}, CN, CO and other molecular bands. We analyze in detail main features of the optical spectra that form in extended gas and dust
envelopes and atmospheric radial velocity pattern measured on all spectral features. The circumstellar envelopes of these stars contain extended halos, arcs, tori, etc. Some stellar envelopes display combinations of these features, and they can possess bipolar or quadrupole circumstellar structures. Optical spectra post-AGB supergiants differ from those of classical high-mass supergiants in the presence of molecular bands overlying the spectrum of the F–G supergiant, anomalies of the H\(_{\text{i}}\), Na\(_{\text{i}}\), and He\(_{\text{i}}\) absorption and emission profiles, and emission lines of some metals (for details see Klochkova (2014)). Moreover, all these spectral properties vary with time.

In general, we see the following types of features in the optical spectra of post-AGB supergiants: 1) symmetric absorption lines with low or moderate intensities, without obvious anomalies; 2) complex neutral-hydrogen line profiles containing time-variable absorption and emission components; 3) absorption or emission bands of molecules, often those containing carbon; 4) shell components...

Figure 1. Profiles of selected split lines in the spectrum of V5112 Sgr taken in August, 02, 2012. The vertical dashed line indicates the systemic velocity \(V_{\text{sys}} = 13\ \text{km/s}\) (Bujarrabal et al. 1992).
of the Na I and K I resonance lines; and 5) narrow forbidden or permitted emission lines of metals formed in the envelope.

The presence of features (2)–(5) is the main difference between the spectra of post-AGB stars and high-mass supergiants.

Our many-year spectroscopic monitoring of post-AGB stars has enabled us to detect a previously unknown characteristic of the spectra of selected post-AGB stars: splitting (or asymmetry) of the strongest absorptions of heavy metals ions (Sr II, Ba II, La II, Y II). This peculiarity has now been detected in the five stars presented in Table 1: CY CMi (Klochkova et al. 2007), V354 Lac (Klochkova 2009; Klochkova et al. 2009), V448 Lac (Klochkova et al. 2010), V5112 Sgr (Klochkova 2013), and CGCS 6918 (Klochkova et al. 2015). The strongest effect is for Ba II ions (see Fig. 1), whose lines with excitation potentials of the lower levels $\chi_{\text{low}} \leq 1$ eV can be split into two or three components. Infrared and radio spectroscopy data are used to show that the stable individual components of split absorptions are formed in structured circumstellar envelopes. Thus, this effect reveals efficient enrichment of the envelope in heavy metals synthesized during the AGB evolution. We suggest that nature of the strong absorption profile (split or asymmetric, number of components) could be related to the morphology and kinematical and chemical properties of the envelope.

The splitting of the profiles of the strongest absorptions of heavy metals detected in the spectra of the supergiants V5112 Sgr, V354 Lac, and CGCS 6918, whose extended envelopes have complex structures, suggests that the formation of a strong, structured envelope in the AGB stage is accompanied by the ejection of stellar nucleosynthesis products into the circumstellar medium. Attempts to find a direct connection between the characteristics of the optical spectrum and the morphology of the circumstellar medium are hindered by the fact that the observed structure of the envelope depends strongly on the inclination of the symmetry axis to the line of site, and also on the spectral and angular resolution of data and images used.

Recall that the so-called diffuse bands (DIBs) well known in the spectroscopy of the interstellar medium are present in the optical spectra of numerous post-AGB stars. But it should be here emphasized that in the spectrum of V5112 Sgr we found several DIBs whose accurate mean (from three spectra) radial velocity is in excellent agreement with the velocity derived from the circumstellar component of the Na I D lines. This leads us to conclude that the diffuse bands are formed in the circumstellar envelope (Klochkova 2013).

We plan to continue in future our spectral research focusing on the fainter post-AGB stars with strong circumstellar envelopes. Complex morphology of envelopes suggests that these stars suffered in the past several events of mass loss due to stellar winds of different rates. It means that we may expect manifestations of stellar nucleosynthesis in their atmospheres and circumstellar environment. For observations of such faint objects we need to improve the efficiency of our observational methods.

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