High–latitude supergiant V5112 Sgr: enrichment of the envelope with heavy s-process metals

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Abstract High–resolution (R = 60 000) echelle spectroscopy of the post–AGB supergiant V5112 Sgr performed in 1996–2012 with the 6-meter telescope BTA has revealed peculiarities of the star optical spectrum and has allowed the variability of the velocity field in the stellar atmosphere and envelope to be studied in detail. An asymmetry and splitting of strong absorption lines with a low lower–level excitation potential have been detected for the first time. The effect is maximal in BaII lines whose profile is split into three components. The profile shape and positions of the split lines change with time. The blue components of the split absorption lines are shown to be formed in a structured circumstellar envelope, suggesting an efficient dredge–up of the heavy metals produced during the preceding evolution of this star into the envelope. The envelope expansion velocities have been estimated to be \( V_{\text{exp}} \approx 20 \) and \( 30 \) km/s. The mean radial velocity from diffuse bands in the spectrum of V5112 Sgr coincides with that from the short–wavelength shell component of the NaI D lines, which leads to the conclusion about their formation in the circumstellar envelope. Analysis of the set of radial velocities \( V_r \) based on symmetric absorption lines has confirmed the presence of pulsations in the stellar atmosphere with an amplitude \( \Delta V_r \leq 8 \) km/s.

Keywords: stellar evolution, post-AGB stars, envelopes, spectra.

1. Introduction
The high-latitude supergiant V5112 Sgr with Galactic coordinates \( l = 23^\circ 98, b = -21^\circ 0 \) and spectral type Sp = F2–F6 (Parthasarathy et al. 1988), identified with the strong infrared source IRAS 19500–1709, belongs to semiregular variable post-asymptotic giant branch (post–AGB) stars. Intermediate mass stars (their initial masses are \( 3–8 M_\odot \)) that evolve from the AGB, losing their matter through a stellar wind, are observed at this short stage. The secular variability of the main parameters observed in post–AGB stars stimulates their spectroscopic monitoring. A spectroscopic monitoring of selected AGB and post–AGB stars has been performed with the 6-meter telescope BTA over the last decade. The main goal of the monitoring program is to reveal a peculiarity and probable variability of the spectrum and to study the temporal behavior of the velocity field in the extended atmosphere and envelope of peculiar supergiants. By now, based on observational data from the 6–m telescope, we have found spectroscopic variability in V510 Pup (Klochkova and Chentsov 2004), BD+48°1220 (Klochkova et al. 2007a), V2324 Cyg (Klochkova et al. 2008a) and the
original results concerning the variability of the optical spectrum and the velocity field in the atmospheres have also been obtained for the variable stars CY CMi (Klochkova 1995; Klochkova et al. 2007b), QY Sge (Klochkova et al. 2007c), V354 Lac (Klochkova 2009; Klochkova et al. 2009), and V448 Lac (Klochkova et al. 2010). The BTA spectroscopy for post–AGB stars is presented in more detail in our review (Klochkova 2012). Recently, Klochkova and Panchuk (2012) published the results of their spectroscopic monitoring for the high–latitude supergiant LN Hya whose observations revealed a peculiarity and variability of the profiles of strong Fe I, Fe II, Ba II, Si II, and other lines. Weak emissions of neutral atoms (VI, MnI, CoI, NiI, FeI) appeared in the June 1, 2010 spectrum. These features of the stellar spectrum detected for the first time suggest that the physical conditions in the upper atmospheric layers of LN Hya changed rapidly in 2010.

This paper is devoted to a detailed study of the optical spectrum for V5112 Sgr. The study of its photometric variability has a fairly long history (Arkhipova et al. 2010; Hrivnak et al. 2011). However, as yet no definitive conclusions about the causes, type, and parameters of the photometric variability have been reached. The cyclic variability amplitude of V5112 Sgr is low; it does not exceed $\Delta V \leq 0.2$ in V and changes with time. As regards the variability period, it has been determined incompletely: as Hrivnak et al. (2010) showed, the dominant period is $38^d$ in V.

A peculiarity of the infrared spectrum for IRAS 19500−1709 is the presence of a peculiar emission feature at 21 $\mu$m (Kwok et al. 1999). The small group of objects with the as yet unidentified 21 $\mu$m emission feature includes post–AGB stars with an atmospheric chemical composition changed in the course of their own evolution. A generalization of the results of several publications appeared in the late 1990’s (Klochkova 1995; van Winckel et al. 1996; Reddy et al. 1997; van Winckel 1997) led Klochkova (1997) and Decin et al. (1998) to conclude that the atmospheric chemical composition of all post–AGB stars with the 21 $\mu$m emission feature changed through the dredge-up of carbon and heavy metals synthesized through the s–process. Subsequent studies of an extended sample of objects confirmed this conclusion. At present, about a dozen post–AGB stars with the 21 $\mu$m emission feature have been studied in our Galaxy. Their main list is contained in Hrivnak et al. (2010), a paper devoted to investigating the photometric variability of this type of stars.

IRAS 19500−1709 is the highest-latitude object in the group of sources with the 21 $\mu$m band. The location of V5112 Sgr at a high Galactic latitude already suggests that it belongs to an old population of the Galaxy. Its low metallicity (van Winckel et al. 1996) confirms this classification. The atmospheric chemical composition of the star studied in detail by these authors is typical of post–AGB stars with the 21 $\mu$m band: the atmospheres of these stars exhibit large overabundances of carbon and s–process elements synthesized during their preceding evolutionary stages. As follows from Table 11 in van Winckel (1997), V5112 Sgr is the record–holder in the overabundances of carbon and s–process elements in the atmosphere.

The circumstellar envelope of V5112 Sgr is also enriched with carbon and is a CO emission source (van der Veen et al. 1993). The flux emitted by the circumstellar envelope in IRAS bands is comparable to the visible flux from this star (Hrivnak et al. 1989). Note that the infrared flux from most of the highlatitude F supergiants is low. In particular, no infrared excess whatsoever was detected in the prototype star, the supergiant UU Her. The supergiant LN Hya, the optical spectrum peculiarities and the velocity field variability in whose
atmosphere were studied by Klochkova and Panchuk (2012), is also a member of this small Galactic population (Sasselov 1984).

As can be seen from the above references, several papers devoted to investigating the chemical peculiarities of V5112 Sgr have been published in the last 20 years, while there is virtually no information about the peculiarities of its optical spectrum and its behavior with time. To make up for this deficiency, we took new high–quality optical spectra for V5112 Sgr in 1996–2012. Analysis of this observational material provided previously unknown information concerning the variability and peculiarities of the star optical spectrum and the detailed picture of radial velocities Vr in its atmosphere and envelope. In this paper, we briefly describe the methods of spectroscopic observations and spectrum processing as well as present and discuss our results.

2. Observations, processing and analysis of spectra

We obtained spectroscopic data for V5112 Sgr at the Nasmyth focus of the 6-m BTA telescope at the Special Astrophysical Observatory with the NES echelle spectrograph designed by Panchuk et al. (2007, 2009). The observations were performed with a 2048×2048–pixel CCD array and an image slicer (Panchuk et al. 2009). The observations on August 2, 2012, were carried out with a larger 2048×4096–pixel CCD, which provided a considerable increase in the recorded spectral range. The spectral resolution is λ/Δλ ≥ 60000; the signal-to-noise ratio is S/N ≥ 100. The mean dates of observations (JD) and the recorded spectral range are given in Table 1.

One–dimensional spectra were extracted from two–dimensional echelle frames using the ECHELLE context of the MIDAS software package modified by Yushkin and Klochkova (2005) by taking into account the peculiarities of the NES optical scheme. Cosmic–ray hits were removed by a median averaging of two spectra taken successively one after another. The wavelength calibration was made with a hollow–cathode ThAr lamp. The extracted spectroscopic data were processed with the DECH20t software package developed by Galazutdinov (1992). Telluric [O I], O2, and H2O lines were used to check the instrumental reconciliation of the spectra for the star and the hollow–cathode lamp. The procedure for measuring the heliocentric radial velocity Vr from the NES spectra and the sources of errors are described in more detail in Klochkova et al. (2008b) and Klochkova and Tavolzhanskaya (2010). The rms measurement error of Vr for stars with narrow absorption lines in the spectrum is ≤1.0 km/s (the accuracy from a single line).

3. Main results

In this section, we describe the main anomalies and variability of the line profiles as well as the related peculiarities in the behavior of the velocity field in the atmosphere and envelope of V5112 Sgr.

The overwhelming majority of absorption features in the stellar spectrum with low and moderate intensities have symmetric profiles without any anomalies. It is these numerous features that we used to study the behavior of the star radial velocities with time. Having analyzed our sets of Vr based on symmetric absorption lines, we concluded that there is no correlation between the line intensity and the corresponding Vr. This allowed us to consider the averaged radial velocities for each spectrum in the subsequent analysis. The mean velocity Vr(metals) reliably determined from numerous symmetric absorption lines is given
Table 1. Log of observations for V5112 Sgr and measured heliocentric radial velocities $V_r$

| Date       | JD          | $\Delta\lambda$, Å | Metals | NaI       | DB        |
|------------|-------------|---------------------|--------|-----------|-----------|
| 05.07.1996 | 2450000+    | 5150–8000           | +14.4±0.5(30) | +21.4–9.6 | −9.1(4)   |
| 07.07.2001 | 2097.51     | 4610–6074           | +21.1±0.1(190) | +21.4–9.6 | −10.5(1)  |
| 14.08.2006 | 3962.34     | 4555–6007           | +5.4±0.1(237)  | +6.8–8.5  | −9.5(1)   |
| 28.09.2010 | 5462.26     | 5165–6690           | +15.4±0.2(99)  | +9.4–9.2  | −9.1(2)   |
| 13.06.2011 | 5725.53     | 4120–5580           | +8.5±0.1(366)  |          |           |
| 02.08.2012 | 6142.42     | 3990–6980           | +10.1±0.1(377) | +9.5–8.8  | −8.8(5)   |

Mean: $-9.0$ $-9.1$

Note. Here, $V_r$ (metals), $V_r$ (NaI), and $V_r$ (DB) are the mean velocities from symmetric absorptions, from the components of the Na I D lines, and from diffuse bands, respectively. The number of lines used to determine the mean velocities is given in parentheses.

in column 4 of Table 1. As follows from this table, $V_r$(metals) changes from date to date with a small amplitude $\leq 8$ km/s relative to the systemic velocity $V_{sys} = 13$ km/s obtained by Bujarrabal et al. (1992) and van der Veen (1993) from CO molecular lines. Obviously, this radial velocity variability with a small amplitude is attributable to the stellar pulsations studied in detail by Hrivnak et al. (2011). Based on a large set of measurements, these authors concluded that the radial velocity of V5112 Sgr changes only slightly near its mean $V_r \approx 14$ km/s, which is very close to the systemic velocity $V_{sys} = 13$ km/s.

The Hα profile. Emission components in the Hα profile are typical of post-AGB stars (see examples in Fig. 2 from Klochkova (1997)) and are among the main criteria for selecting such objects (Kwok 1993). As follows from Fig. 1, the Hα profile contains emission components in all our spectra for V5112 Sgr. An Hα profile with a double–peaked emission feature typical of post–AGB stars was recorded in 2010 and 2012. Having analyzed a large volume of spectroscopic observations for post–AGB stars near the Hα line, Sanchez Contreras et al. (2008) classified the profiles of these stars. Using their classification, we attribute the Hα profile in the spectrum of V5112 Sgr in quiescent phases to the EFA (emission–filled absorption) type. According to universally accepted views, this profile type points to the existence of a long–lived circumstellar gas reservoir. The line width is determined primarily by the effect of scattering by free electrons and by the kinematics of the circumstellar structure.

Note the abrupt change of the Hα profile type in the spectrum of V5112 Sgr that occurred at the turn of the new century: in 1996, we recorded a profile inverse to the P Cyg one, while in the 2000s, as follows from Fig. 1, the profile contained already two emission components. We emphasize that this change of the Hα profile type that we detected occurred concurrently with a significant change in the object photometric characteristics found by Hrivnak et al. (2010) during a long–term monitoring.

The radial velocity derived from the absorption components of neutral hydrogen lines changes with time (Fig. 1). However, the small number of measurements (from one to four for different HI lines) did not allow us to reveal any regular patterns in the behavior of $V_r$(HI).
Figure 1. Hα profiles in the spectra of V5112 Sgr taken at different dates from Table 1: August 2, 2012 (solid line) and September 28, 2010 (dash–dotted line). The crosses plot the profile in the spectrum with resolution $R = 25000$ taken on July 5, 1996, with the Lynx spectrograph (Panchuk et al. 1993). Here and in subsequent figures, the vertical dashed line indicates the systemic velocity $V_{\text{sys}} = 13\, \text{km/s}$.

**Strong absorption lines.** Analyzing our high-quality spectra of V5112 Sgr taken in a wide wavelength range, apart from the variable Hα profile, we revealed other, previously unknown, peculiarities of the spectrum.

First, we found the strongest absorption lines of metals (Si II, Ba II, Y II, Zr II) originating in the star high atmospheric layers to have anomalous profiles: asymmetric with an extended blue wing or split into individual components. As an example, Fig. 2 presents fragments of the spectra with BaII 4554 and BaII 4934 Å lines in the August 2, 2012 and July 7, 2001 spectra, respectively. Anomalous split profiles of the resonance lines for various chemical elements are shown in Figs. 3 and 4. A different width of the components is clearly seen here: for the long–wavelength component, it is approximately twice the width of the short–wavelength ones shifted considerably relative to the systemic velocity. This difference in widths suggests that the long–wavelength and blueshifted components are formed under different physical conditions. Note line splitting can also be seen in that Ba II 4934 Å the fragment of the spectrum for V5112 Sgr from van Winckel (1997).

It should be emphasized that profile anomalies were detected only for the absorption lines of those metals for which large overabundances were detected in the stellar atmosphere. At the same time, the profiles of even the strongest absorption lines of ironpeak elements have
Table 2. Radial velocity \( V_r \) from three components of the Ba II lines in the spectra of V5112 Sgr taken at different dates

| Date       | \( V_r \), km/s | \( \text{BaII} \) | \( \text{metals} \) | \( \text{metals} \) |
|------------|-----------------|-------------------|-------------------|-------------------|
| 07.07.2001 | −17.3           | −8.7              | +20.5             | +21.07            |
| 14.08.2006 | −14.9           | −5.6              | +4.6              | +5.37             |
| 13.06.2011 | −16.4           | −5.9              | +10.9             | +8.48             |
| 02.08.2012 | −17.0           | −7.8              | +11.28            | +10.12            |

*Note. The mean velocity inferred from the symmetric absorptions of metals from Table 1 is given in the last column for comparison.*

Figure 2. Fragments of the spectra for V5112 Sgr containing split lines. The Ba II 4554 Å line in the August 2, 2012 spectrum (left); the Ba II 4934 Å in the July 7, 2001 spectrum (right). The identification of main absorption lines is indicated.

no anomalies. This can be clearly seen in Fig. 2 from our comparison of the Ba II and Fe II lines with similar intensities.

Second, comparison of the line profiles in the spectra of V5112 Sgr taken on different nights revealed significant variability of the profile shape and positions of the split–line components. To illustrate the variability effect, Fig. 3 presents the profiles of two Ba II lines with the most prominent profile asymmetry and variability for several dates of observations.

Consider in more detail the picture of radial velocities based on the components of split absorption lines. Table 2 presents \( V_r \) for the individual components of the Ba II lines for four dates of observations. As follows from our comparison of the data from the last two columns of this table, the positions of the long–wavelength components of the Ba II lines change synchronously with those of the symmetric absorptions. Thus, we have reason to believe that the red component of the Ba II lines is formed in the stellar atmosphere. The position of the blue component itself changes only slightly with time, deviating from the mean \( V_r \approx −16.2 \text{ km/s} \) by \( ±0.6 \text{ km/s} \). Thus, given the systemic velocity \( V_{\text{sys}} = 13 \text{ km/s} \), we find that the short–wavelength component of the Ba II lines (and other split absorption lines) is formed in layers expanding with a velocity \( V_{\exp}(1) \approx 30 \text{ km/s} \).
Here, it is important to note that a similar expansion velocity, $V_{\text{exp}} \approx 30–40 \text{ km/s}$, was found by Bujarrabal et al. (1992) based on the recording of the CO emission profiles in the millimeter spectrum of IRAS 19500$–1709$ associated with the star V5112 Sgr. Bujarrabal et al. (1992, 2001) emphasize that the profiles of the CO bands for IRAS 19500–1709 are two–components ones: a central narrow emission component originating in a medium with a low (about 10 km/s) expansion velocity is superimposed on a high–velocity component. In our optical spectra, the split absorption line profiles also exhibit a second component located between the short–wavelength and atmospheric ones: for the Ba II lines, the velocity corresponding to the position of the middle component is, on average, $V_r \approx -7.1 \text{ km/s}$. Thus, we obtain the following estimate for the expansion velocity of the layers in which this component is formed: $V_{\text{exp}}(2) \approx 20 \text{ km/s}$.

**The Na I resonance doublet** was detected for four dates of observations. As follows from Fig. 5 and the data from columns 5 and 6 of Table 1, the doublet D line profile is complex. Two components are reliably identified at our spectral resolution. The position of the long–wavelength component of the Na I D lines changes with time, being in agreement with the positions of the symmetric metal absorptions originating in the stellar atmosphere for each date. In contrast, the position of the short–wavelength component of the Na I D lines is essentially constant with time. The mean velocity determined from the short–wavelength component is $V_r \approx -9.0 \text{ km/s}$, which is close to the position of the middle component in the split Ba II lines. Obviously, this stable short–wavelength component of the Na I D lines is formed in the circumstellar envelope, because we cannot expect the presence of interstellar Na I lines in the spectrum of a star so far away from the Galactic plane. Bartkevicius (1992) gives the
Figure 4. Profiles of selected split lines in the August 2, 2012 spectrum of V5112 Sgr.

color excess $E(B-V) = 0.10$ in the catalog of UU Her stars. The multiband photometry of V5112 Sgr performed by Hrivnak et al. (1989) is also indicative of a low reddening.

A complex profile that also contained the circumstellar component, in addition to the photospheric and interstellar ones, in the spectra of post–AGB stars with envelopes was previously observed only for the D lines of the Na I doublet. In particular, this is also true for the star V354 Lac, in the spectrum of which the circumstellar component of the Na I D lines was identified by Reddy et al. (2002). The profile of the Na I D lines and other peculiarities of the spectrum for this star were studied in more detail by Klochkova (2009) and Klochkova et al. (2009) based on BTA spectra. The circumstellar absorption components of the Na I D lines were also identified in the spectrum of HD 56126 that was well studied by Bakker et al. (1997), Klochkova et al. (2007b), and Klochkova and Chentsov (2007). In addition, the cases of a manifestation of the circumstellar gaseous–dusty envelope in the form of emission components of the Na I D lines are known. As an example, we provide spectra for the star V510 Pup identified with the infrared source IRAS 08005–2356 (Klochkova and Chentsov 2004), the bipolar nebula AFGL 2688 (Klochkova et al. 2004), and the semiregular variable QY Sge = IRAS 20056+1834 (Kameswara Rao et al. 2002; Klochkova et al. 2007c).

We emphasize also that weak absorption features identified with the so–called diffuse bands (DBs) well known in the spectroscopy of the interstellar medium are present in the optical spectrum of V5112 Sgr. As an illustration, Fig 5 presents the profiles in “intensity–radial velocity” coordinates for one of the bands at 6195.96 Å in two spectra. The choice of this band is dictated by the fact that it is narrow and least blended in the spectra of F– and G–supergiants. Because of the large intensity difference between the absorption features, the scales of the vertical axes differ approximately by a factor of 10. This figure suggests that
the positions of the circumstellar component of the Na I D2 line and the 6195.96 Å band coincide.

In the wavelength range 5780–6613 Å, we measured Vr(DB) from the positions of the reliably identified 5780, 5797, 6196, 6234, and 6379 Å features. We took the exact wavelengths of these bands from the list by Hobbs et al. (2008). In the August 2, 2012 spectrum, the equivalent widths of these features are W = 83, 40, 30, 8, and 18 Å, respectively. The inaccuracy of the mean velocity determined in the spectra of V5112 Sgr is \( \leq \pm 0.5 \) km/s. As follows from the last row in Table 1, the mean (over the spectra) Vr(DB) = −8.9 km/s is in excellent agreement with the velocity derived from the short-wavelength component of the Na I D lines.

The derived coincidence suggests that the weak diffuse bands we detected originate in the circumstellar envelope. This fact is not so trivial as it may seem, because after the publication of the results by Luna et al. (2008), it has been widely believed that the diffuse bands originate only in the interstellar medium; the physical conditions in the circumstellar envelopes of post–AGB stars are not conducive to their formation. Luna et al. (2008) reached this conclusion by studying high-resolution spectra for a sample of post–AGB stars. We compared our measurements of W and Vr with the data of these authors for V5112 Sgr and point out satisfactory agreement in W. However, the measurements of Vr for V5112 Sgr from Luna et al. (2008) have a low accuracy due to the inclusion of the wide band at 6284 Å,
Table 3. Basic information for four related post-AGB stars

| Star   | 21\(\mu\) | \([\text{C/Fe}]\) | Envelopes structure | CO | \(V_{\text{exp}}, \text{km/s}\) |
|--------|------------|-----------------|-------------------|----|------------------|
| CY CMi | +          | +               | halo              | 10–12 (L1993) | 11 (K2007) |
| V5112 Sgr | +      | +               | bipolar           | 8, 11–14.4 (L1993) | 20 30 (this paper) |
|         |           |                 |                   | 10, 30–40 (B1992) |
| V354 Lac | +       | +               | bipolar           | 9.6–11.6 (L1993)  | 10.8 (K2009) |
| V448 Lac | +       | +               | halo + arcs       | 14–15 (L1993)     | 15.2 (K2010) |

Note to the table. The overabundances of carbon \([\text{C/Fe}]\) and heavy metals \([\text{s/Fe}]\) are marked by + in column 2 in accordance with the results from Klochkova (1995) for CY CMi, van Winckel et al. (1996) for V5112 Sgr, Klochkova et al. (2009) for V354 Lac, and Decin et al. (1998) for V448 Lac. The type of circumstellar envelope morphology (column 4) is given according to the Hubble space telescope observations by Sahai et al. (2007). The expansion velocities \(V_{\text{exp}}\) in column 5 are given based on CO band observations. The last column gives the expansion velocity determined from the positions of the Swan \(C_2\) molecular bands in the optical spectra of CY CMi, V354 Lac, and V448 Lac and from the shell components of the Ba II lines for V5112 Sgr. The references are designated as L1993 for Loup et al. (1993), B1992 for Bujarrabal et al. (1992), K2007 for Klochkova et al. (2007b), K2009 for Klochkova et al. (2009), and K2010 for Klochkova et al. (2010).

which, besides, is blended with telluric features, and the use of the band at 6613.7 Å, which is located in the blue wing of a very strong Y II absorption line in the spectrum of V5112 Sgr. Yttrium has a large overabundance in the stellar atmosphere: according to van Winckel (1997), \([\text{s/Fe}] = +1.3\). Therefore, the 6613.7 Å line profile has anomalies typical of the strong absorption lines of heavy metals in the spectrum of V5112 Sgr.

### 4. DISCUSSION

As we have pointed out above, an optical manifestation of circumstellar envelopes has been found previously in the D lines of the Na I doublet. The results of observations of the circumstellar envelopes around Mira–type stars in the K I 7665 and 7669 Å lines are also known (see Guilain and Mauron (1996) and references therein). Based on high–resolution spectra, apart from Na I and K I, Mauron and Huggins (2010) also detected other metals in the gas phase in the Mira–type star CW Leo (the infrared source IRC+10216), which has an extremely extended structured envelope with an angular size of about 200 arcsec: Ca I, Ca II, and Fe I.

In this work, we have detected a manifestation of the envelope in lines of heavy metals in the spectrum of a star at a later evolutionary stage for the first time. The main new result of our study is the detection of a multicomponent Ba II line profile and an asymmetry of the low–excitation absorption lines for a number of other metals in the spectrum of V5112 Sgr. Previously, we found a distortion of the profiles of the strongest absorption lines for three more post–AGB stars with similar parameters: CY CMi = IRAS 07134+1005, V354 Lac = 22274+5435, and V448 Lac = 22223+4327.

Table 3 gives basic properties for these related post–AGB stars. In addition to the common signatures of protoplanetary nebulae (PPN) formulated by Kwok (1993), a further study of these stars and associated infrared sources revealed a number of important properties. In
particular, an emission feature at $\lambda = 21\mu$ was detected in the infrared spectra of all four objects being compared. The $21\mu$ band was first detected in the infrared spectra of four PPNs by Kwok et al. (1989); a decade later, the same authors (Kwok et al. 1999) published a list of already a dozen PPN, among which there are also the four stars from Table 3. Based on high–spatial–resolution Hubble space telescope snapshots, Sahai et al. (2007) and Ueta et al. (2000, 2008) concluded that the envelopes of these four stars have different aspherical morphologies (see column 4 in Table 3). The last two columns in this table give the expansion velocity $V_{\text{exp}}$ of the circumstellar envelope from millimeter (column 5) and optical (column 6) observations.

Among the objects listed in Table 3, the semiregular variable V354 Lac (spectral type G5 Iap, as inferred by Hrivnak (1995)) is closely analogous to V5112 Sgr in envelope structure and spectrum peculiarities. The spectroscopic monitoring of this star performed by Klochkova et al. (2009) at the 6-m BTA telescope with resolution $R = 60000$ revealed a splitting of the strongest absorption lines with a lower–level excitation potential $\chi_{\text{low}} < 1$ eV. Analysis of the kinematics showed that the short–wavelength component of the split line is formed in the star extended gas–dust envelope. This splitting is most clearly seen in the profile of the Ba II 6141 Å line with an equivalent width $W \approx 1$ Å. The Doppler separation between the absorption components of this line is about $35$ km/s. The position of the short–wavelength component of Ba II coincides with the position of the circumstellar component in the profile of the Na I D-lines, which is formed in the same layers where the Swan C$_2$ molecular bands are also formed. This coincidence suggests that, apart from the atmospheric component, the complex Ba II 6141 Å line profile contains the component originating in the circumstellar envelope. Such a splitting (or asymmetry of the profile because of the flatter blue wing) is also observed for other Ba II lines ($\lambda 4554$, $5853$, and $6496$ Å) as well as for the strong La II 6390 Å, Nd II 5234 Å, 5293 Å, Y II 5402 Å, lines. In the spectrum of V354 Lac, the lines of these heavy–element ions are enhanced to an extent that their intensities are comparable to those of the neutral hydrogen lines.

Based on BTA spectra, Klochkova et al. (2007b) and Klochkova et al. (2010) found peculiarities and variability of the optical spectra for two other stars from Table 3, CY CMi and V448 Lac, respectively. The profiles of the strongest metal absorption lines in the spectrum of these two stars are asymmetric. All lines, except the hydrogen ones, have the same type of asymmetry: the blue wing is more extended than the red one, i.e., the radial velocity measured from the upper part of the profile (from the wings) turns out to be lower than that measured from the core. The blueshift of the wings relative to the core increases as the line strengthens, gradually or abruptly. In addition, we see from our comparison of the spectra taken at different dates that the profile shape of these lines originating in the star expanding atmosphere (at the base of the wind) changes both with time and with line intensity. We emphasize that no clear splitting into components has been found in the collection of BTA echelle spectra for CY CMi and V448 Lac even for the most intense absorption lines. The expansion velocity was measured with a high accuracy for both stars from several tens of rotational lines of the Swan C$_2$ molecular bands and it was concluded that the molecular envelope expansion is stable.

Note that a probable splitting of the absorption lines into components with different positions and intensities for different dates of observations must not be ruled out a priori. Observations with an ultra–high spectral resolution are needed to test this assumption.

The difference in profile peculiarity type for two pairs of stars, V5112 Sgr and V354 Lac with split profiles of the strongest absorption lines of selected elements as well as CY CMi
and V448 Lac with asymmetric but unsplit profiles, suggests that a complex morphology of the circumstellar envelope could be a factor causing the profile peculiarity and variability for strong lines. We see from the data in Table 3 that the envelope for the pair of V5112 Sgr and V354 Lac with split absorption lines is bipolar, while for CY CMi and V448 Lac there is no splitting and the extended envelopes have a less distinct structure. The validity of this assumption is also confirmed by the fact that in the spectrum of V5112 Sgr, for which Bujarrabal et al. (1992) detected slow \( V_{\text{exp}} = 10 \text{ km/s} \) and fast \( 30-40 \text{ km/s} \) expansion based on CO bands, we see a three–component profile structure for strong absorption lines. The split line profiles include the photospheric and two shell components, one of which, by analogy with the CO profile, originates in the envelope formed at the AGB stage and expanding with a velocity \( V_{\text{exp}}(2) \approx 20 \text{ km/s} \) and the other originates in the envelope with an expansion velocity \( V_{\text{exp}}(1) \approx 30 \text{ km/s} \) formed later.

At present, there are no universally accepted views of the formation of deviations from spherical symmetry for PPN. An asymmetry (in particular, bipolarity) of the structures in selected PPN was detected in several types of observations. Having investigated the polarization of the near–infrared emission for a sample of extended nebulae, Gledhill et al. (2001) identified three different shapes of these objects: isotropic, bipolar, and nebulae with a dominant core. IRAS 19500–1709 in polarized light is a typical bipolar nebula with two lobes and a dust lane. Having analyzed high–spatial–resolution HST optical images for a sample of PPN, Ueta et al. (2000, 2008) concluded that the optical thickness of the circumstellar matter is a decisive factor in the formation of a particular type of stellar envelope morphology.

A brief overview of the physical mechanisms for the formation of these complex structures can be found, for example, in Lagadec et al. (2011). As a rule, it is assumed that the dense spherical envelope formed at the AGB stage expands with a low velocity, while the axisymmetric part of the envelope formed later, at the post–AGB stage, undergoes fast expansion. The sequence of these processes gives rise to a gradient of the optical thickness in the direction from the equator to the polar axis of the system. The existence of a companion in the system and/or the presence of a magnetic field can also be the physical factors due to which the spherical symmetry of the stellar envelope is lost in the short interval of evolution between AGB and post–AGB (see Huggins et al. 2009; Leal–Ferreira et al. 2012; and references therein). Recently, Koning et al. (2013) proposed a simple PPN model that was constructed based on a pair of evacuated cavities inside a dense spherical halo. The authors showed that all of the morphological peculiarities observed in real bipolar PPNs could be reproduced by varying parameters (the matter density in the cavity, its size and orientation).

As Sahai et al. (2007) pointed out, the difference in the shape of “extended halo” and “bipolar” nebulae could be purely visual, because the observed shape depends strongly on the inclination of the axis to the line of sight and on the angular resolution of the structure. For instance, according to Nakashima et al. (2009), the extended envelope of CY CMi has no clear structure in the form of jets, cavities, etc.

In future, it is especially important to study with a high resolution \( R \geq 60000 \) the optical spectra of other related stars from the sample of objects with the 21 \( \mu \) emission feature with atmospheres enriched with heavy s–process metals. In particular, this also applies to the faint stars with carbon enriched envelopes identified with the infrared sources IRAS 04296+3429 and 23304+6147. According to the data by Klochkova et al. (1999, 2000), the atmospheres of the central stars of both sources are enriched with carbon and heavy metals, while according
to the observations by Sahai et al. (2007), the envelope of IRAS 04296+3429 has a bipolar shape and the envelope of IRAS 23304+6147 probably has a quadrupole shape.

5. Conclusions

Based on our high-resolution echelle spectra of the post-AGB supergiant V5112 Sgr taken in 1996–2012 at the 6-m BTA telescope, we detected peculiarities and variability of the spectrum and the velocity field in the stellar atmosphere and envelope. An asymmetry and splitting of strong metal absorption lines, which is maximal for the Ba II lines whose profile is split into three components, have been found for this star for the first time. The profile shape of the split lines and their positions are variable in time.

We determined two envelope expansion velocities $V_{\text{exp}} \approx 20$ and $30 \text{ km/s}$ consistent with the picture of envelope expansion from millimeter observations. The coincidence of $V_r$ determined from the short-wavelength components of the split absorption lines with the velocities derived from CO molecular bands and the short-wavelength component of the Na I D lines suggests that the short-wavelength components of the heavy-metal lines are formed in a structured circumstellar envelope. Thus, evidence for an efficient dredge-up of the heavy metals produced during the stars preceding evolution into the envelope has been obtained for the first time.

Analysis of the set of radial velocities $V_r$ inferred from symmetric absorption lines confirmed the presence of pulsations in the stellar atmosphere with a pulsation amplitude $\Delta V_r \leq 8 \text{ km/s}$.

The mean (from three spectra) radial velocity determined from diffuse bands in the spectrum of V5112 Sgr agrees excellently with the velocity derived from the short-wavelength shell component of the Na I D lines. This leads us to conclude that the diffuse bands are formed in the circumstellar envelope.

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