Time resolved spectroscopy of BD+46°442: gas streams and jet creation in a newly discovered evolved binary with a disk*

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ABSTRACT

Context. Previous studies have shown that many post-AGB stars with dusty disks are associated with single-lined binary stars. The inferred orbital separations are too small to accommodate a fully-grown AGB star, therefore, these systems represent a new evolutionary channel that bypasses a full AGB evolution.

Aims. To verify the binarity hypothesis on a larger sample, to reveal the nature of the companions, and to probe the disk structure and eventually the disk formation mechanisms, we started a high-resolution spectral monitoring of ~40 field giants whose binarity was suspected based on either a light curve, an infrared excess, or a peculiar chemical composition.

Methods. Starting from the spring of 2009, we monitor the program stars with a new fiber echelle spectrometer HERMES. We measure their radial velocities (RVs) with a precision of ~0.2 km s⁻¹, perform detailed photospheric abundance analyses, and analyze the time-resolved high-resolution spectra to search for line-profile variability.

Results. Here we report on the discovery of the periodic RV variations in BD+46°442, a high-latitude F giant with a disk. We interpret the variations due to the motion around a faint companion, and deduce the following orbital parameters: \( \beta_{\text{orb}} = 140.77 \pm 0.02 \), \( e = 0.083 \pm 0.002 \), \( a \sin i = 0.31 \) AU. We find it to be a moderately metal-poor star \([M/H] = -0.7\) without a strong depletion pattern in the photospheric abundances. Interestingly, many lines indeed show periodic changes with the orbital phase: Hα switches between a double-peak emission and a P Cyg-like profiles, while strong metal lines appear split during the maximum redshift. Similar effects are likely visible in the spectra of other post-AGB binaries, but their regularity is not always realized due to sporadic observations.

We propose that these features result from an ongoing mass transfer from the evolved giant to the companion. In particular, the blue-shifted absorption in Hα, which occurs only at superior conjunction, may result from a jet originating in the accretion disk around the companion and seen in absorption towards the luminous primary.

Key words. Stars: abundances – binaries: spectroscopic – Stars: individual: BD +46°442 – Stars: circumstellar matter – Stars: AGB and post-AGB – ISM: jets and outflows

1. Introduction

Recently van Aarle et al. (2011) investigated the spectral energy distribution (SED) of optically bright candidate post-asymptotic giant branch (post-AGB) stars in the Large Magellanic Cloud. Surprisingly, they found that in about half of candidates, the SED indicates that the circumstellar material, which is the relic of the AGB mass loss, is not in the form an exanding envelope, but rather in the form of a stable, likely Keplerian, disk.

In our own Galaxy, post-AGB stars with disks are common as well (e.g. de Ruyter et al. 2006), but statistics of Galactic post-AGB stars are less complete, and the lack of well constrained distances (hence, luminosity) makes the interpretation of these numbers more difficult. Galactic sources, however, have an obvious advantage of being closer and easier to study.

The leading hypothesis explaining the envelope bifurcation into the outflows and the disk types, is that disks form only around binaries. The observational foundation comes from the fact that indeed, many disc sources in our Galaxy turned out to be single-lined binaries (e.g. van Winckel et al. 2009, and references therein). Presumably disk formation happens through an interaction with the companion when the more massive component becomes a red giant (RG) or an asymptotic giant branch (AGB) star (van Winckel 2003). The process itself is poorly understood. Livio & Soker (1988) and Sandquist et al. (1998), among others, showed that a circumbinary disk could be a remnant of a common envelope created when the Roche lobe of an AGB star engulfs a companion. Other scenarios were proposed by e.g. Mastrodemos & Morris (1999), where a disk-like structure is created in a wind-accretion scenario or perhaps as a result of the AGB wind and the accretion jets interaction (Akashi & Soker 2008).

The impact of the disk onto the system cannot be underestimated. Many of the Galactic and even LMC post-AGB disk objects show a peculiar chemical photospheric composition that resembles the gas phase of the interstellar medium (ISM): elements of higher condensation temperature, such as iron, are less abundant than volatiles (e.g. Gridhar et al. 2005, Maas et al. 2005, Gielen et al. 2009, Sumangala Rao et al. 2012). This is believed to be a result of pollution from a disk, which may have
already dissipated in some systems and therefore has no foothold in the SED. In the disk, refractory elements nucleate into dust grains, which are segregated from the gas, and the depleted gas falls back onto the star (Waters et al. 1999). On one hand, this effect helps to identify current or former disk systems, but on the other hand masks the original metallicity of the stars and the eventual products of the AGB dredge-ups, complicating the identification of the evolutionary stage.

At a later evolutionary stage, as was proposed by Waelkens et al. (1996) and Jorissen (1999), a disk system may turn into a Barium star, when the current post-AGB primary evolves into a white dwarf (WD) and supposedly a main sequence (MS) companion into a red giant. Barium stars are binary systems where a red giant bears signs of contamination by the nuclear-synthetic products (such as Barium) by the former AGB companion (now a WD). By adopting the formalism of Lubow (2010), and references therein, Dermine et al. (2010) explored the binary-disk interaction regime relevant in Barium stars and showed that circumstellar disks may be important at pumping the eccentricities of Barium stars relative to the observed values.

The Galactic objects with known orbits cannot have evolved on single-star evolutionary tracks: typical AGB star has a radius ~1 AU, while many post-AGB binaries with a disk have smaller separations, which brings a possibility that these systems started interacting already at the red giant stage. Some of the objects may have never gone through the AGB stage, unless the interaction resulted in the orbit shrinkage. With the observed periodicities, the full AGB evolution must be shortcut and this is corroborated by the finding that the majority of disk sources have oxygen-rich photospheres and disks dominated by crystalline silicates (Gielen et al. 2008, 2011). Another ambiguity pertaining the evolution of these systems is whether the stars will still show up as planetary nebulae (PNe), with the circumstellar material locked in a disk. While binarity helps to explain bipolar PNe, the periods of binary stars in PNe are at least two orders of magnitude shorter than in the disk post-AGB systems (De Marco 2009).

The theories of disk formation cannot predict timescales for disk re-accretion and dissolution either. The insight can be gained by gathering information on the inner-most regions of the disk from optical and near-IR spectroscopy. Previous spectroscopic studies of post-AGB stars explored mainly stellar radial velocities (RVs) and the basic properties of both the photosphere and the disk. Only briefly did they touch on the signs of activity at the star-to-disk interface, such as emission in Hz or circumstellar absorptions in the Ca II H&K and Na I D lines, and the interpretation was usually that these features trace a subsiding AGB wind. The notion was that after a circumbinary disk is formed, the system enters a passive evolution as a detached binary. No success has been achieved at uncovering gas re-accretion (with only one tentative detection of the winnowing gas by Hinkle et al. 2007). In none of the systems, the companion is detected so far. To explore the details of the disk-star interaction, systematic time-resolved investigation of the disk and chemically-peculiar post-AGB systems is therefore highly desirable.

A literature compilation of Galactic post-AGBs was assembled in the Toruń catalog (Szczepanek et al. 2007) and consists of ~400 objects. In this catalog, 51 source have been identified as disk sources in De Ruyter et al. (2006), and this number has increased ever since. About two dozen post-AGBs of De Ruyter et al’s list have been identified to be single-lined spectroscopic binaries with periods from 115 to 2600 days and orbital separations from 0.1 to 3.6 AU. The latest addition can be found in van Winckel et al. (2009) who photometrically and spectroscopically monitored a selection of low-amplitude pulsators from the southern hemisphere. All low-amplitude pulsators are binaries, but the suspected binary nature of the remaining 60% of De Ruyter et al’s list remains to be established. This is an observational challenge, because many objects show large amplitude pulsations making the interpretation of radial velocity variations not straightforward (e.g. Maas et al. 2002).

In the spring of 2009, we started a high-resolution spectroscopic monitoring programme on 34 Galactic post-AGB candidates with disks and a few objects without the IR excess, that are observable from the northern hemisphere, using a newly built optical echelle spectrograph HERMES (Raskin et al. 2011). These objects were required to satisfy at least two of the following criteria: an IR excess characteristic of a disk, an RV Tau-like variability, variability suggesting a possible obscuration by a disk, low surface gravity combined with the location away from the Galactic plane, deficiency in the refractory elements. In this paper we report on one of the first new short-period binaries that we uncovered after three years of observations. BD+46°442 (SAO 37487, IRAS 01427+4633) is a poorly-studied V = 9.5 high-latitude Galactic F giant (b = 15°), not known to be variable in RV or photometry. It was selected in our survey due to the strong infrared excess characteristic for disk objects, as originally measured by the IRAS satellite. The paper is organized as follows: after description of the data (Sect. 2), we present results of the abundance analyses of BD+46°442 (Sect. 3), then model its SED (Sect. 4), the radial velocity (RV) curve (Sect. 5), and examine the behaviour of the hydrogen and some metal lines (Sect. 6). In the Discussion section, we compare the discovered periodic spectral variations with those in other post-AGB systems and in interacting binaries, and discuss theories capable to explain this behaviour.

2. Observations and data reduction

Each target in our on-going post-AGB survey is observed about twice per month during the visibility season. This program is part of a much broader effort to study binary interaction processes in evolved stars (van Winckel et al. 2010). The main goal is to measure RVs to detect and characterize the orbital motion. For brighter targets, additional studies are performed, such as determination of abundances, rotation velocities, and the circumstellar features. The spectra are obtained with the fiber-fed echelle spectrograph HERMES, attached to the Flemish 1.2 m telescope Mercator on La Palma, Canary Islands. The spectrograph is optimized for high resolution, stability, and broad wavelength coverage. This is achieved primarily by implementing an image slicer, an anti-fringe CCD coating, and a thermal enclosure (Raskin et al. 2011).

Sixty spectra of BD+46°442 were obtained during three seasons of observations in 2009 – 2012. We used a fiber configuration that provides a resolution R = 80,000 – 90,000 over the wavelength range ∆λ = 3800 – 9000Å. The exposure times varied between 500 – 1800 s while the signal-to-noise ratio (S/N) between 20 – 90 (as measured near 6500 Å). Nightly calibrations consisted of two sets of biases, flats, and the Th-Ne-Ar 2

1 http://www.ncac.torun.pl/postagb2
are spectra obtained in the evening and in the morning. To reduce a particular object frame, the nearest set was used. At least one IAU radial velocity standard was observed nightly and occasionally a series of arcs, to monitor the fluctuations in the zero-point of the wavelength calibration. These tests showed that the typical uncertainty on the absolute value of the RV is ∼0.2 km s⁻¹ and is mainly caused by the pressure fluctuations in the instrument room (Raskin et al. 2011). The data reduction was performed with a dedicated Python-based pipeline, that outputs extracted, cosmic-ray cleaned, wavelength calibrated, and order-merged spectra.

3. Atmospheric analysis

3.1. Atomic data and model atmospheres

Our atmospheric analysis of BD+46°442 is based on the comparison with synthetic profiles of hydrogen lines and on the equivalent-width (EW) measurement of metal lines. The latter were obtained using the DECH20 code by Galazutdinov (1992), that provides a convenient interface for the continuum normalization, and the EW measurement by means of a Gaussian fit or a direct integration. Line identification was carried out using the following on-line resources: Spectroweb stellar atlas by Lobel (2008, 2011) for λ < 6800 Å, and the Solar atlas by Delbouille et al. (1968) in combination with the Atomic line database by P. Van Hoof for the longer wavelengths.

The line list used for the abundance determination was provided by V. Kovtyukh (2010, private communication) and is mainly based on the version published in Kovtyukh & Andrievsky (1999). We also follow the procedure for the determination of the surface gravity (log g) and the micro-turbulent velocity (Vₜₜₑ) from the latter work. Our choice is dictated by the fact that yellow supergiants studied by Kovtyukh & Andrievsky (1999) spectroscopically are very similar to post-AGB stars. To convert EWs to abundances, we use the local thermodynamical equilibrium (LTE) radiative transfer code MOOG by C. Sneden with the ATLAS9 model atmospheres that include the updated opacity distribution functions by Castelli & Kurucz (2003).

Kovtyukh & Andrievsky (1999) obtained the bulk of their oscillator strengths (log g f s⁻¹) by adjusting the laboratory values in such a way, that they could reproduce the solar abundances of Grevesse et al. (1996) from the EWs measured in the solar spectrum of Kurucz et al. (1984). They used a canonical solar model of 5777/4.438/1.0 (Tₑₑ / log g / Vₜₜₑ) from the set of the original ATLAS9 models of Kurucz (1992) and his WIDTH9 LTE code. We found that this combination of the older atmospheric models and the code tends for the lines of a given element to produce systematically slightly different abundances than our combination of the atmospheric models and code, both for the Sun and BD+46°442. Therefore, when giving abundances of BD+46°442 relative to the Sun (X/H), we introduced small corrections (up to ±0.08 dex) in the solar abundances of Kovtyukh & Andrievsky (1999) to compensate for this difference.

3.2. Photospheric parameters

Since there is no information on the reddening or the photometric variability in BD+46°442, we decided to derive all photospheric parameters spectroscopically. For this we analyzed a S/N∼130 spectrum obtained by averaging the best quality spectra numbers 3 and 4 from the same night (Fig. 1). The visual examination of all the spectra did not reveal any obvious variations in their effective temperature (Tₑₑ). Variations in the cores of strong lines have been detected, which we attribute to the circumstellar matter (Sect. 6), but those lines were not used in the EW analysis (we only used lines with EWs ≤ 170 Å). This single spectrum, therefore, should give a good representation of the basic photospheric parameters of our star.

First, we confirmed a spectral type F from Simbad by comparing our spectrum to the spectral libraries of R. O. Gray and of the VLT-UVES (Bagnulo et al. 2003). Then we computed from our EWs the iron abundance, by adopting a range of model parameters expected for an F1-III star: Tₑₑ = 6200 – 8000 K, log g = 0.5 – 4.0, and Vₜₜₑ = 0 – 12.0 km s⁻¹, first using the ATLAS9 models with the solar metallicity ([M/H] = 0) and later with [M/H] = −0.5 to match the subsolar metallicity obtained in the final iteration. To perform an excitation analysis, we plotted the iron abundances against the EW and the excitation potential of the lower level (ɛ), separately for the Fe I and Fe II lines, to examine possible trends. Correct (LTE) atmospheric parameters are obtained when all the lines give the same value of the abundance. Trends with the EW can be removed by tuning Vₜₜₑ, while agreement between the average abundances derived from the Fe I and Fe II lines (the ionization balance) indicates a correct log g. Iron lines are usually used in this method because they are the most numerous, but the same values of Vₜₜₑ and log g should in principle hold for all the elements.

At sub-solar metallicities and gravities, however, neutral species become underpopulated compared to the LTE case, due to the UV over-ionization and the decreased rate of collisions, resulting in the positive corrections that need to be added to the LTE abundances (Rentzsch-Holm 1998; Bergemann 2011; Mashonkina et al. 2011). Observationally this is manifested in the fact that in supergiants, Fe I lines require smaller values of Vₜₜₑ, and log g to bring their abundances in agreement with the better behaved Fe II lines (which is the dominant ionization state in F-G stars), as shown for example by Kovtyukh & Andrievsky (1999) for the classical Cepheid δ Cep and in Takeda et al. (2007) for some post-AGB stars. We find the same effect for BD+46°442. Following recommendations in the literature, we use the Fe II lines for the determination of Vₜₜₑ, while for the determination of log g we extrapolate abundances from the Fe I lines to EW = 0, as weak lines are less susceptible to non-LTE effects. Following this procedure, we found a correlation between the adopted Tₑₑ and the derived log g/Fe/H. To break this degeneracy, we turn to the Balmer and Paschen hydrogen lines.

Hydrogen lines have the advantage over the metal lines that to first order they do not depend on the metallicity. Furthermore, we can consider the shape of the extended wings in addition to the line depth when comparing to the synthetic profiles. We compared Balmer lines in BD+46°442 to the synthetic profiles of Coelho et al. (2005) and Paschen lines to those of Munari & Castelli (2000). Ha was not considered, as it shows...
Fig. 1. Sample of the spectrum of BD+46°442 obtained on 2009/08/17 compared to the HERMES spectrum of Polaris. While Hβ is similar in both stars, indicating similar temperature and gravity, metal lines are noticeably weaker (and broader) in BD+46°442, indicating a sub-solar metallicity.

Fig. 2. Hydrogen lines in BD+46°442 (black dots) compared to the best fitted of the available synthetic profiles (grey solid lines), that were computed with $T_{\text{eff}} = 6250$ K, log $g = 2.0$, [M/H] = −0.5. To match the resolution of the model Paschen lines, the observed profiles were convolved to $R = 20,000$, while Balmer lines are shown at the native HERMES resolution of 85,000.

a strong non photospheric contribution at all phases. From the Paschen lines we chose to consider only Pa14 and Pa17 as the least blended ones. We noticed that the Paschen break in the models is too deep compared to BD+46°442 and other supergiants we have studied; therefore, before making a comparison, we had to normalize the model and the observed profiles at the pseudo-continuum regions between the neighboring lines.

In the parameter space considered here, model hydrogen lines strengthen both with higher $T_{\text{eff}}$ and lower log $g$ (Fremat et al. 1996; Munari & Castelli 2000). Fortunately, a stronger sensitivity of Paschen lines to gravity allowed to exclude log $g \geq 3.0$, and $T_{\text{eff}} > 6500$ K along with it. No Paschen models are available for log $g < 2.5$ for the range of temperatures considered here, but they would require $T_{\text{eff}} < 6000$ K, which is too low to fit Balmer lines. We therefore adopt $T_{\text{eff}} = 6250 \pm 250$ K, log $g < 3.0$ (Fig. 2), and return to the iron lines to put a better constraint on log $g$. Our estimate is further confirmed by a good match of Paschen lines and the shape of Hβ wings between BD+46°442 and Polaris (Fig. 1). Polaris Aa is a well-studied short-period Classical Cepheid, for which e.g., Usenko et al. (2005) inferred $T_{\text{eff}} = 6000 \pm 170$ K, log $g = 2.2 \pm 0.3$, and [Fe/H] = +0.07.

Finally, $T_{\text{eff}}$ is also frequently derived from the requirement that the iron abundance derived from the Fe I lines does not depend on $\chi$. Applying this criterion to BD+46°442, we obtain $T_{\text{eff}} = 7500$ K, which is consistent with the hydrogen fits. However, as we discussed above, Fe I lines may not be reliable in our star due to non-LTE effects. Fe II lines, on the other hand, do not cover a large enough range of excitation potentials. We thus restricted ourselves to $T_{\text{eff}} = 6000$, 6250, 6500 K and, using the EW analyses of iron lines, deduced the following combinations of log $g$/V$_{\text{tur}}$ for these temperatures: 1.0/4.0, 1.5/4.0, 2.0/4.0, with precision of 0.5 dex in log $g$ (set by the model step size), and 1 km s$^{-1}$ for V$_{\text{tur}}$. Our final best model of 6250/1.5/4.0 is shown in Fig. 5. Linear fits to the Fe II and Fe I abundances plotted against EWs (and extrapolated to EW=0 for Fe I) give 6.74 ± 0.07 and 6.76 ± 0.06 for the iron abundance, respectively. The other two best-fit models are used for the estimation of the model-dependent errors on the abundances.

3.3. Abundances

The abundances of all elements deduced from the individual lines using our best model atmosphere are shown in Fig. 6. The elements are arranged in order of increasing condensation temperature to verify the presence of the depletion pattern reported in the literature for many disk sources. The average abundances per element and the error budget are shown in Fig. 5 and in Table 1. Given possible non-LTE effects, we assigned a quality flag to each element (each ionization state), that reflects the reliability of the final abundance estimate: flag 1 (best) – ions that do not show a trend with EW; flag 2 – neutrals for which at least three lines with EW≤50 mÅ were available for averaging; flag 3 (least reliable) – all other cases. These flags are reflected in the circle sizes in Fig. 5. The errorbars are the RMS values, they result from the uncertainties in the EW measurement and the values of log $g$/s. Table 1 also gives systematic errors due to the uncertainties in the model parameters. Singly-ionized species are only weakly sensitive to variations in $T_{\text{eff}}$ and V$_{\text{tur}}$ compared to the neutral ones, but are more sensitive to log $g$.

It is easy to see a moderate metal deficiency in BD+46°442, at the level of −0.5...−0.7 dex, compared to the Sun. Apart from the slightly more abundant C and S, however, there is no obvious trend with $T_{\text{cond}}$. The α-process elements (Si, S, Mg, Ti) show a 0.1–0.3 dex enhancement over the iron group, while s-process
Fig. 6 compares photometric observations of BD+46°442 Spectral energy distribution without chemical depletion (Reddy et al. 2006). Overall this is a typical composition of a thick disk star derived in Sec. 3.2. The total reddening of the preferred model and the observed optical and near-infrared fluxes. When we selected BD+46°442 during the first and the second dredge-ups, but can also be affected by the non-LTE effects. The lower panel is less conclusive due to the non-uniform coverage of the excitation potentials by the Fe II lines. The dashed line indicates the iron abundance of the Sun.

The presence of the excess emission beyond 2 µm is obvious. When we selected BD+46°442 for our sample, we could only rely on the IRAS detection of the excess (of which the 100 µm flux is still an upper limit), and now it is confirmed with the two other space missions, AKARI (Ishihara et al. 2010) and WISE (Wright et al. 2010). The SED, which is clearly not double-peaked and only slightly reddened, argues against a simple detached shell distribution for the circumstellar material. Instead, the SED of this kind is characteristic of a star surrounded by a passive disk (e.g. in de Ruyter et al. 2006, Gielen et al. 2007).

We modeled the SED of BD+46°442 with MCMax (Min et al. 2009), a 2D Monte Carlo radiative transfer disk code. This code computes the temperature structure and density of the disk. The vertical scale height of the disk is computed by an iteration process, demanding vertical hydrostatic equilibrium. For the input stellar model we use the parameters as discussed in Section 3 and adopt a total system mass $M_\ast = 2 M_\odot$ and a typical post-AGB luminosity of $L_\ast = 2000 L_\odot$ (corresponding to a distance for the system of 3.3 kpc). Since we lack information on the exact mineralogy of the dust in the disk, we use a mixture of astronomical silicates and metallic iron, with grain sizes ranging from 0.1 to 100 µm. The adopted gas-to-dust ratio is kept fixed at 100. The geometry of the disk is determined by the inner and outer radii $R_{\text{in}}$ and $R_{\text{out}}$, the total dust mass $M_{\text{dust}}$, and the power law of the surface-density distribution of the dust $\Sigma \sim R^{-p}$.

To keep the numbers of free parameters for the model low, we keep the outer radius fixed at $R_{\text{out}} = 500$ AU, and use a value $0.5 < p < 2.0$ for the surface-density distribution, as expected in a disk environment. To account for the low observed total reddening, the inclination is kept fixed at 15°. This modeling is quite degenerate and equally well fitting models with slightly different sizes, total masses and surface-density distributions can be found. Complementary measurements, such as interferometric observations and infrared spectroscopy, would be invaluable to constrain further the disk geometry and mineralogy.

In Fig. 6 we show a disk model which gives good agreement with the photometric data. The disk parameters for this model are: $R_{\text{in}} = 7$ AU, $R_{\text{out}} = 500$ AU, $p = 1.6$, and $M_{\text{dust}} = 2 \times 10^{-6} M_\odot$. For the dust composition we use a combination of amorphous olivine and metallic iron, in a ratio of ∼96%/4%. The AKARI and IRAS fluxes past 30 µm cannot be fit by this model because that part of the SED requires even larger dust grains than adopted. These large grains are likely not uniformly mixed in the disk, but must have settled towards the mid-plane. Modeling such process is beyond the scope of our investigation.

BD+46°442 thus belongs to a distinct group of evolved stars surrounded by dusty disks (Gielen et al. 2011). To verify whether it is a binary system, and whether the disk is circumstellar or circumbinary, we analyze the radial velocities.
5. RV curve

We measured RVs using a cross-correlation method with a mask representing a G2 star. The mask consists of ~1100 lines. Cross-correlation functions (CCFs) extracted from each order were averaged, and the resultant profile was fitted with a Gaussian to determine the RV. Some asymmetries in the CCF were noted that appear to correlate with the orbital phase (see discussion in the following section). They, however, were never large enough to affect the location of the main peak. The measured velocities are given in Table A.1 and plotted in Fig. 7. Errors in the RV consist of two quadratically added terms: the error of the Gaussian fit of two quadratically added terms: the error of the Gaussian fit to the CCF, near-constant temperature, and the large displacement of a very good Keplerian solution with only one point (spectrum 23) out of 60 deviating by more than 3σ (Fig. 8). The derived orbital parameters are given in Table 2. The errors on the parameters were estimated via the Monte Carlo method, using 1000 simulated RV sets. For a given date a value for the RV was drawn from a Gaussian distribution with a mean and σ equal to the observed RV value and its error, respectively. For every simulated

Table 1. Chemical composition of BD+46°442.

| Z | Ion | log ε | [X/H] | RMS | Δ[X/H] | N | flag |
|---|-----|-------|-------|------|--------|---|------|
| 6 | C I | 8.11  | −0.41 | 0.09 | −0.05  | 6 | 2    |
| 7 | N I | 7.89  | −0.04 | 0.18 | +0.02  | 2 | 3    |
| 11| Na I| 5.79  | −0.53 | 0.08 | −0.09  | 2 | 3    |
| 12| Mg I| 6.92  | −0.66 | 0.35 | −0.07  | 2 | 3    |
| 13| Al I| 6.32  | −0.15 | –    | −0.09+0.09| 1 | 3    |
| 14| Si I| 7.09  | −0.45 | 0.16 | −0.08+0.07| 8 | 2    |
| 16| S I | 6.67  | −0.45 | 0.08 | −0.06+0.06| 3 | 2    |
| 20| Ca I| 5.51  | −0.85 | 0.08 | −0.11+0.12| 5 | 2    |
| 21| Sc II| 2.38 | −0.77 | 0.15 | −0.25+0.26| 4 | 1    |
| 22| Ti I| 4.40  | −0.61 | –    | −0.17+0.16| 1 | 3    |
| 22| Ti II|4.27 | −0.74 | 0.17 | −0.25+0.24| 13| 1    |
| 23| V II|3.30  | −0.67| 0.16 | −0.23+0.23| 3 | 1    |
| 24| Cr I|4.75  | −0.86| 0.13 | −0.17+0.16| 3 | 2    |
| 24| Cr II|4.86 | −0.73| 0.10 | −0.17+0.18| 9 | 1    |
| 25| Mn I|4.52  | −0.86| 0.12 | −0.14+0.14| 3 | 2    |
| 26| Fe I|6.59  | −0.88| 0.20 | −0.13+0.13| 39| 2    |
| 26| Fe II|6.75 | −0.73| 0.15 | −0.18+0.19| 25| 1    |
| 28| Ni I|5.37  | −0.86| 0.13 | −0.14+0.13| 15| 2    |
| 29| Cu I|2.89  | −1.32| –    | −0.20+0.21| 1 | 3    |
| 30| Zn I|3.72  | −0.85| –    | −0.16+0.18| 3 | 1    |
| 39| Y II|1.03  | −1.19| 0.12 | −0.27+0.27 | 3 | 1    |
| 40| Zr II|1.79 | −0.79| –    | −0.25+0.25 | 1 | 3    |
| 56| Ba II|1.40 | −0.73| –    | −0.31+0.30 | 1 | 3    |
| 60| Nd II|1.07 | −0.49| –    | −0.28+0.29 | 1 | 3    |
| 63| Eu II|0.02 | −0.48| –    | −0.26+0.27 | 1 | 3    |

Notes. Abundances are given for our best photospheric model $T_{eff}/\log g/V_{ turb} = 6250/1.5/4.0$. Δ[X/H] designates abundance changes corresponding to the changes in $T_{eff}/\log g$ of $–250 K/–0.5$ dex (case A) and $+250 K/+0.5$ dex (case B), which are our second best atmospheric model estimates. The flag designates the quality of the N lines used in the averaging: from 1 for the best cases to 3 for the worst. Elements with flag 3 had less than 3 lines with EW ≤ 50 mÅ.
and the coe-
parameters indicating the goodness of the RV fit (reduced chi-squared)
the real data. An example application of this procedure for the
orbital period and eccentricity is given in Fig. 9. As one can see,
of the RV variations in BD
zero.
albeit small (0.08), the eccentricity is significantly di-
Notes.
Fig. 7. HERMES radial velocities of BD+46°442 plotted against
Keplerian orbit with parameters listed in Table 2.
Table 2. Orbital elements of BD+46°442

| Parameter   | Value  | σ     |
|-------------|--------|-------|
| P (d)       | 140.77 | 0.02  |
| a sin i (AU)| 0.31   | 0.001 |
| f(m) (M_⊙) | 0.19   | 0.001 |
| K (km s⁻¹) | 23.66  | 0.06  |
| e           | 0.08   | 0.002 |
| ω (°)       | 100    | 2     |
| T₀ (JD)     | 2 455  | 0.6   |
| γ (km s⁻¹) | -98.96 | 0.04  |
| χ²          | 0.19   | 0.001 |
| σ           | 99.83% |

Notes. Orbital parameters with their uncertainties and two statistical parameters indicating the goodness of the RV fit (reduced chi-squared and the coefficient of determination).

dataset the orbital parameters were obtained, and their scatter was used as an error estimate on the parameters obtained from the real data. An example application of this procedure for the orbital period and eccentricity is given in Fig. 7. As one can see, albeit small (0.08), the eccentricity is significantly different from zero.

Our observations provide the first account as far as we know of the RV variations in BD+46°442, that we successfully reproduce with a Keplerian orbit. BD+46°442 proves to be yet another evolved system with a disk that is a binary. The semi-major axis of the primary is at most 1.2 AU (for i = 15°). This is smaller than the silicate dust sublimation radius that would be at 2 AU (given Lₚ = 2000 L_⊙), and much smaller than the actual inner disk radius at 7 AU estimated from the fit to the NIR excess with metallic iron particles. This barely leaves space for a circumstellar dusty disk around any of the binary components, unless the gas is very optically thick to shield some radiation. We conclude that the dusty disk producing the IR excess is circumbinary rather than circumstellar.

Fig. 8. Upper panel: radial velocities of BD+46°442 phased with a period of 140.77 days and overlaid on our Keplerian fit. The horizontal line marks the corresponding systemic velocity. The φ = 0 was defined to correspond to the maximum RV (i.e. near one of the elongations). Bottom panel: residuals from the fit with ±3σ margins.

6. Line profiles

6.1. Hα

In Fig A.1 we show that Hα alternates between two major profiles: a double-peak emission with peaks separated by ~100 km s⁻¹ and wings stretching to ±200 km s⁻¹, and a P Cyg-like profile. This is better illustrated in Fig 10 (medium left panel) where we depict Hα after subtraction of the model photospheric profile. The resulting profile shows both emission and absorption components that vary in strength with the orbital phase. The double-peak emission is observed most of the time, but is strongest and most symmetric between φ = 0.7 – 0.8, corresponding to the giant’s inferior conjunction (when it is between us and the companion, Fig. 11). When the giant starts to retreat, the emission diminishes, while the central absorption blue-shifts and broadens, quickly turning into a P Cyg profile. The expansion velocities reach 350 km s⁻¹ at φ = 0.3 – 0.4 when the companion is in front. Higher members of the Balmer series develop two major components that vary in strength with the orbital phase.

6.2. Non-photospheric components of metal lines

In the other panels of Fig 10 (and in Fig. A.2) we show the CCF and a representative set of metal line profiles. As expected, the CCF follows the behaviour of weak to medium-strong lines, like Ca II 8912 Å, that constitute the majority of unblended lines in the CCF list. These lines are “well behaved”, being symmetric and hardly variable, except for the RV that reflects the orbital motion of the giant. The Fe II(42) triplet, on the other hand, presents an example of strong lines (EW≥300 mA) that show...
Fig. 10. Dynamic spectra of selected lines and the CCF as a function of the orbital phase (time runs from top to bottom). Colours designate continuum-normalized fluxes (except for H$_\alpha$), with black corresponding to the strongest absorption. Fluxes in the missing phases were obtained by a linear interpolation between the nearest observed phases. Dotted vertical line marks the systemic velocity, while the horizontal dashes on the left – the observed phases. One orbital period is shown twice to guide the eye. H$_\alpha$ is plotted after subtraction of the photospheric model spectrum; solid and dashed lines represent the RV curves (original and $\pm 50$ km s$^{-1}$ offset) of the giant and of the putative companion to illustrate the lack of significant motion in the emission component. Only data from the first two seasons of observations are shown (spectra 1-25, obtained between July 2009 - January 2011); later observations confirm the general behaviour with phase, but the intensities of the circumstellar features appear to vary slightly from cycle to cycle.
Fig. 9. Distribution of the orbital period and eccentricity values obtained from 1000 simulated RV data sets. The solid cross marks the solution based on the observed RVs (see Table 2), while the dotted cross and the upper right panel show an alternative solution with a slightly better $\chi^2$ derived from the simulated RV data sets.

an additional narrow component near $V_{\text{syst}}$. It is best seen when the giant retreats from us ($\phi = 0.9 - 1.1$), while in the opposite phase it appears less prominent, being either weaker or blue-shifted (by $\sim 10$ km s$^{-1}$ from $V_{\text{syst}}$) and overlapping with the photospheric component. Other similar cases involve strong lines of Ba II, Ca II, Fe I, Fe II, Mg I, and Ti II, and the resonance lines of K I. Exceptions include the prominent O I triplets at 7775 and 7778 Å, that still show normal, single-deep, profiles. These transitions, however, require much higher excitation ($\chi_{\text{low}} = 7 - 9$ eV) and form deeper in the atmosphere. The strengthening of the central absorption between $\phi = 0.8 - 1.25$ and the disappearance or blue-shift between $\phi = 0.3 - 0.7$ resemble the behaviour of the central absorption in H$\alpha$. H$\alpha$ absorption, however, is more blue-shifted, particularly in the P Cyg phase.

Na I D lines also show a central absorption component, but also an additional, narrower one $13$ km s$^{-1}$ to the blue from $V_{\text{syst}}$, which coincides with the centroid of H$\alpha$. Both components are probably of circumstellar origin, but it is difficult to study them due to blending with the photospheric lines. To the red, there are three supposedly ISM components, at RV$ = -23$, -13, and $-1$ km s$^{-1}$, that are stable in RV and depth. They are also observed in the resonance K I lines. Using a code provided in Reid et al. (2005), we calculated kinematic distances to the foreground clouds responsible for these components. The largest distance is obtained for the most blue-shifted component ($V_{\text{helio}} = -23$ km s$^{-1}$, $V_{\text{LSR}} = -18$ km s$^{-1}$), which is $1.25 \pm 0.5$ kpc. Taking this as a minimum distance to BD+46°442 itself, and correcting for the reddening $A_V = 0.56$, we obtain a lower limit on the stellar luminosity: $M_V = -1.54^{+0.19}_{-0.08}$. Clearly, the star is brighter than normal FG giants of the luminosity class III ($M_V = 1 \ldots 2$), but is consistent with being an F type post-AGB star, which have $M_V = -2 \ldots -3$ (Bond 1997; Ginestet & Carquillat 2002). On the other hand, the two components at $V_{\text{helio}} \sim -100$ km s$^{-1}$ would indicate an Iab supergiant ($M_V = -6 \ldots -7$) at more than 2.5 kpc above the Galactic plane, which is very unlikely. Thus, the two components near $V_{\text{syst}}$ are most likely circumstellar.

In addition to the absorption components, as can be seen from Fig. 10 near $\phi = 0.75$ corresponding to the giant’s inferior conjunction, weak emission appears in the wings of the sodium lines, echoing H$\alpha$. We observe only one other system of emission lines beside H$\alpha$ and Na I D: the weak Fe I(12) multiplet at 8047.6 and 8075.1 Å. Similar to the central absorption of metal lines, the emission is centered on the systemic velocity and does not participate in the orbital motion (Fig. 10).

6.3. Secondary spectrum?

The metal lines noticeably strengthen near the giant’s inferior conjunction ($\phi = 0.75$). Zooming in on the wings of the CCF (see the right-bottom panel of Fig. 10), however, reveals also faint absorption spectrum moving in anti-phase with the giant’s spectrum. Therefore, we may be observing a companion spectrum instead. We remodeled the CCF profiles with two Gaussians, where possible, and obtained a semi-amplitude of 15±5 km s$^{-1}$ for the secondary spectrum. Dividing by the 23.7 km s$^{-1}$ of the primary, we obtain a mass ratio of 0.6. Given this mass ratio and the mass function of 0.2, we obtain the individual masses of 0.9–0.3 $M_\odot$ for the giant and 1.4–0.5 $M_\odot$ for the companion for a range of inclinations between 45–90°. These masses are consistent with a low-mass pair where the originally more massive component has evolved into a post-AGB, while the companion is still on the MS or in the sub-giant stage. Using expressions for the Roche-lobe radius from Paczyński (1971), that depend only on the mass ratio, we obtain for the giant $R_1 \approx 0.37 \times (a_1 + a_2) = 57 - 39R_\odot$. The radius of BD+46°442 matches this range well if it has a typical post-AGB luminosity of 2000-3000 $L_\odot$. Therefore, we are observing an interacting system where the post-AGB star is (close to) filling its Roche-lobe and as such feeding a more compact companion.

We want to stress, however, that these are very preliminary estimates. The depth of the secondary component in the CCF is about 1% (compared to 10% of the giant’s spectrum), which is far below the typical S/N ratio of our spectra. The presence of this component thus can not be verified from individual lines. Furthermore, the spectral type of the companion can not be significantly different from that of the primary, otherwise one would not detect it with the G2 mask. The companion then should be only ten times fainter than the giant primary, which is too bright were it a MS star. And if both components are giants, they would have to have nearly identical initial masses due to the short longevity of the giant stage. It is possible instead that we are seeing a pseudo-photosphere of an accretion disk around the companion rather than the companion’s spectrum itself. Higher S/N spectra and a multi-band photometry are needed to confirm the contribution of the companion in the system’s flux.

7. Discussion

The discovery of the RV variations in BD+46°442 provides a strong support for the disk-binary connection in post-AGB stars. With a period of 140.77 ± 0.02 d it is one of the shortest known post-AGB binaries. A small but significant eccentricity indicates that the system is not completely circularized. In the following
7.1. \( \text{H}_\alpha \) variability in interacting binaries

The \( \text{H}_\alpha \) profiles discussed here are not uncommon among post-AGB stars [Waters et al. 1993b; Pollard et al. 1997; Maas et al. 2003; Sánchez Contreras et al. 2008], but they have not been systematically studied for variability in function of orbital phase. We are aware of four other disk systems where a strong blue-shifted absorption was noted to develop during the giant’s superior conjunction: HR 4049 with \( P_{\text{orb}} = 430 \pm 6 \text{ AU, } i = 60^\circ, e = 0.3 \) (Waalkens et al. 1993); Van Winckel et al. 1995; Bakker et al. 1998); HD 44179 (the central star of the Red Rectangle nebula) with \( P_{\text{orb}} = 318^\circ, a \sin i = 0.5 \text{ AU, } i_{\text{effective}} = 35^\circ, e = 0.4 \) (Waalkens et al. 1996; Witt et al. 2009); IRAS 08544–4431 with \( P_{\text{orb}} = 508^\circ, a \sin i = 0.4 \text{ AU, } i = 60^\circ, e = 0.2 \) (Maas et al. 2003; Derou et al. 2007; Van Winckel et al. 2008); IRAS 19135+3937 with \( P_{\text{orb}} = 127^\circ, a \sin i = 0.2 \text{ AU, } e \sim 0.3 \) (Gorlova et al. 2012). The fact that BD+46°442 has a very small eccentricity \( (e = 0.083 \pm 0.002) \) indicates that the cause of the spectral variations most likely lies in the varying line of sight towards the components, rather than in the physical changes during the orbital motion, such as an increased mass loss at periastron.

The most common interpretations of the double-peak \( \text{H}_\alpha \) emission in stellar spectra are: an inclined Keplerian gaseous disk (e.g. in Be and T Tau stars), the giant’s atmosphere that is irradiated by a hot companion (Cataclysmic Variables, symbiotics), propagating shock in pulsating stars (Miras, RV Tau stars), and the chromosphere. There is no indication in our spectra of a hot companion (no helium lines or nebular emission), pulsations are excluded based on the smooth orbital RV curve, and the existence of chromospheric activity has yet to be established in post-AGB stars. We therefore concentrate on the disk hypothesis. The emission could originate in the gaseous extension of the circumbinary dusty disk towards the center of the system or in a circumstellar disk around one of the components. To differentiate between these possibilities we searched for similarities with other types of interacting binaries. There, a disk sometimes forms around a more compact companion as a result of the Roche-lobe overflow or a wind accretion from a larger companion.

In Algols, when the binary separation is large, the accretion stream from a cool giant curves and settles into a disk around a more massive hot MS primary (Richards & Albrittain 1999). The simulations of Miller et al. (2007) show that the dominant source of \( \text{H}_\alpha \) emission in Algols is the disk, while the stream provides a much smaller contribution. A similar situation could be occurring in BD+46°442, only the accreting companion is much fainter than the giant (Fig. 11). The problem with this interpretation of the \( \text{H}_\alpha \) emission is the lack of convincing motion in the anti-phase with the absorption spectrum of the primary (Fig. 10). The P Cyg-like profile, on the other hand, is a signature of an outflow. It is very rare to find such broad absorption feature (with velocities up to \( -300 \text{ km s}^{-1} \)) in Algols, and it may not be observed in every cycle (Peters 1989; Miller et al. 2007). Usually Algols display classical and inverse P Cyg-like profiles at a smaller range of velocities just before and after giant’s inferior conjunction, which is explained by the disk eclipse. This is clearly not the case in BD+46°442 where the wind profile is strongest near the giant’s superior conjunction. The explanation of the P Cyg profile, therefore, should be searched elsewhere.

W Ser systems are thought to be in the stage preceding Algols, when the transfer rate is very high and the accretion disk completely obscures the accretor. In at least one such system, \( \nu \) Ser with \( P_{\text{orb}} = 137^d \) (Netolík et al. 2009), a P Cyg-like profile is observed near the giant’s superior conjunction, which Nariai (1967) explained by a “coronal stream” from the giant to the companion. At this orbital phase the stream is directed towards us and at the same time is projected against the giant (Fig. 11), creating a blue-shifted absorption. Furthermore, in the simulations of interacting binaries the accretion stream is often found to be curved in the direction of the giant’s motion, which could explain why the largest speeds in BD+46°442 are reached at a slightly later phase after the conjunction (compare spectra 6 and 7 on Fig. A.1). Interestingly, \( \nu \) Ser is considered to be a non-eclipsing type of W Ser stars. In classical, edge-on, systems the blue-shifted absorption is not observed, perhaps because the accretion stream, when projected against the donor, is hidden from our view by the accretion disk.

Symbiotic stars are another relevant class of objects to consider. There double-peaked emission profiles are quite common (Van Winckel et al. 1993), and are being interpreted as either due to an accretion disk around a WD (Robinson et al. 1994; Van Eck & Jorissen 2002) or a disk wind (Skopal 2006). There are even reports that the blue peak gets suppressed at the orbital phase corresponding to the occurrence of the P Cyg-like profile in BD+46°442 (Robinson et al. 1994; Mürset et al. 2000), but the true broad absorption in symbiotics is only observed in outbursts.

7.2. Jet launching in the accretion disk of the companion

Summarizing, the variations of \( \text{H}_\alpha \) in BD+46°442 are complex, but can be decomposed into several time-dependent properties for which we need an explanation. 1) The double-peaked emission is rather stable in velocity along the orbit, which means that it is connected to the system itself and not to one of the components. The emission, however, varies in strength, being strongest during the giant’s inferior conjunction. 2) The P Cyg-like absorption component is observed at very high velocity, but only during a very short orbital phase interval, when the giant is at the superior conjunction (see Fig. 10). As we have seen in the previous section, some of these aspects can be explained by the interaction with the companion.

It is useful to compare this behaviour to the line variability as observed and discussed in HD 44179 by Witt et al. (2009). Witt et al. (2009) attributes both emission and absorption in \( \text{H}_\alpha \) to the same structure, which is a jet launched from the accretion disk of the companion. P Cyg-like profile forms when the blue-shifted lobe becomes projected against the face of the giant, which is impossible for the red-shifted lobe and which is therefore always observed in emission. The jet launched in a precessing accretion disk around the companion of HD 44179 may have created the Red Rectangle nebula (Velázquez et al. 2011). This model can be adopted for BD+46°442 (Fig. 11), with one caveat. Red Rectangle is a peculiar system, because the optical flux is dominated by scattering as our line of sight is in the orbital plane of the binary, allowing to see both jets at a range of inclinations. For BD+46°442, on the contrary, the smaller IR excess indicates that we are observing the star directly, along the line-of-sight which is not in the orbital plane. The small line-of-sight reddening shows that our aspect angle towards the system is not through the puffed-up circumbinary disk. The blue absorption as seen at conjunction is created by the blue-shifted jet which is projected on the giant only in this specific orbital phase.
Continuum photons coming from the giant will be scattered outside the line-of-sight by Hα resonant scattering on high velocity hydrogen atoms in the jet. The Doppler shift of 300 km s$^{-1}$ corresponds to the line-of-sight velocity component and needs to be deprojected to obtain the outflow velocity of the jet. As we do not constrain the jet opening angle, nor the angle between the jet axis of symmetry and the orbital plane, the deprojected velocity is difficult to quantify. The static double-peak emission still requires a different origin, as discussed in the previous section.

The existence of jets has been strongly advocated based on other independent arguments in e.g., a β Lyrae system [Harmanec 2002, Ak et al. 2007], a proto-type of the massive Roche-overflow binaries (of which W Ser is a sub-class). Jets have been invoked to explain bipolar planetary and proto-planetary nebulae (PPNe), including the Red Rectangle [Cohen et al. 2004, Velázquez et al. 2011]. Sahai et al. (2002) detected a proper motion of jets in the PPNe Henize 2-90 with velocity of a few hundred km s$^{-1}$, which is consistent with the Keplerian velocity at the surface of a low- to intermediate-mass MS star. Finally, jets have been also mentioned in symbiotics, in regard to symmetric bumps at ±1000 km s$^{-1}$ appearing in outbursts [Skopal et al. 2009], though they have never been invoked to explain the double-peak profile of the quiescent state. It is difficult to include jets in the hydrodynamical calculations due to the supersonic velocities, or in the radiative transfer calculations. Nevertheless, the possibility of jet contribution into Hα and Hβ formation was demonstrated in several studies [Budaj & Richards 2004, Arrieta et al. 2005].

7.3. Gas stream

Further phenomenological similarity between BD+46°442 and the mass-exchanging binaries can be seen in the non-photospheric “shell” components of metal lines. The narrow features, mostly in absorption, discussed in BD+46°442 (such as the Fe II (42) and the near-IR Ca II triplets), have been first noted in fast rotating hot stars [Slettebak 1986]. They originate from the meta-stable levels at 2–4eV above the ground state, and therefore must form in a low-density, but hot (several kK) circumstellar medium. In cooler stars, shell components have been mostly studied in the resonance Ca II H&K and Na I D lines, but these transitions are prone to interstellar contamination. Because of their regular behaviour with the orbital phase in BD+46°442, we again consider them to originate in the binary flows, rather than in some clumps in the circumbinary disk (an explanation proposed for the protoplanetary disks, see e.g. Mora et al. 2004). The behaviour of these features appears to be very diverse from system to system, so it is not surprising that they were ascribed to a whole range of accretion-related structures: disk, disk-wind collision shocks, jets, streams, etc. (e.g. Andersen et al. 1988, Plavec 1988, Weiland et al. 1995, Miller et al. 2007, Sudar et al. 2011, Mennekent & Smith 2010, Harmanec 2002, Quiroga et al. 2005).

We found a particularly good agreement between the behaviour of the metal absorptions in BD+46°442 with HeI lines in a W Ser-type star RY Scuti ($P_{orb} = 11^d$, orbital separation ~0.2 AU), as described in Grundstrom et al. 2007. To explain these features, one needs gas projected on the giant over at least half of the period and moving with a slower velocity, for example a circumbinary Keplerian disk. Furthermore, this ring must have an asymmetric density distribution to explain unequal strength of the absorption in elongations. Grundstrom et al. 2007) proposed that this structure could in fact be a plume on the trailing side of the giant, an outflow from the L2 point that extends beyond the orbital plane and wars around the system (Fig. 11). It explains why the central absorption is clearly visible when the giant recedes from us, but is much less pronounced in the opposite elongation. This outflowing arm is consistently reproduced in the hydrodynamical simulations of interactive binaries [de Val-Borro et al. 2009, Mohamed & Podsiadlowski 2011]. Grundstrom et al. 2007) further speculate that the outflows through the L2 and L3 points could explain the formation of the large nebula (R~2000 AU) surrounding RY Scuti. This scenario brings an intriguing possibility of the current formation of the circumbinary disk around BD+46°442. Finally, in a recent study, Thomas et al. 2011) reports on the identical behaviour of some metal lines, including Fe II 4924 Å, in HD 44179. Unlike Grundstrom et al. 2007), they interpret it in terms of the photospheric line asymmetries due to matter outflowing from the giant near periastron and falling back near apastron. This model, however, is questionable for BD+46°442 due to its low eccentricity. Obviously, observations of more systems with different eccentricities and orbit orientation are needed to test these hypotheses.

Another manifestation of the circumbinary gas around BD+46°442 are two weak emission lines of the Fe I(12) multiplet in the far red region of the optical spectrum. These emission lines have been reported at least in two other disk post-
AGB sources, 89 Her (a binary with $P_{orb} = 288^d$, $a \sin i = 0.1$ AU, $i = 15^\circ$, $e = 0.2$, and a resolved bipolar CO outflow, see Waters et al. 1999, Bujarrabal et al. 2007) and a candidate RV Tau star QY Sge (Kameswara Rao et al. 2002). In 89 Her these lines are narrow (FWHM $<10$ km s$^{-1}$) and single-peaked, while in QY Ser and BD+46$^\circ$442 they are much broader (FWHM $\sim 40$ km s$^{-1}$) and perhaps even double-peaked. Unfortunately, the latter is difficult to measure accurately for BD+46$^\circ$442 due to contamination with telluric absorption. Kameswara Rao et al. (2002) proposed that this emission originates in the bipolar wind from the system, in particular, from the gas within the inner cavity of the circumbinary disk that re-emits starlight scattered by the disk walls. Assuming a total stellar mass for BD+46$^\circ$442 of 1.5 $M_\odot$ and a circumbinary gas disk with Keplerian rotation, the HWHM=20 km s$^{-1}$ indicates a distance of 3.3 AU. Given that the inner radius of the dusty disk is at 7 AU, as deduced from the SED fitting, this gas can indeed be located within the inner disk hole. Kameswara Rao et al. (2002), also explained broader emissions in H$\alpha$ and the Na I D lines as originating in the same wind, only further out from the disk plane where the wind has been accelerated. This scenario would explain the lack of the RV variations in the emission lines of BD+46$^\circ$442, including H$\alpha$. The remaining differences between 89 Her and QY Sge with BD+46$^\circ$442 could be due to different inclination angles. To constrain the latter for BD+46$^\circ$442, an accurate light-curve is needed.

The next obvious step to confirm the association of all these circumstellar features with binarity, would be a systematic comparison of disk sources to the sources with spherical shells (as inferred from the SED, e.g. van Aarle et al. (2011)), as the latter presumably harbor single stars.

8. Summary

We obtained 60 echelle spectra over a period of 3.5 years for BD+46$^\circ$442, a poorly-studied high-galactic giant with a dusty disk. We derive the following photospheric parameters: $T_{\text{eff}} = 6250 \pm 250$ K, $\log g = 1.5 \pm 0.5$, and an average metallicity [M/H] = $-0.7 \pm 0.2$, without a strong depletion pattern. The enhanced abundance of $\alpha$ elements is characteristic of the original composition of a thick-disk low-mass star, consistent with a post-AGB interpretation. The observations do not show a dependence of the observed features on orbital parameters: an orbital period of 140.8 days, an eccentricity $e = 0.08$, and separation $< 1$ AU. This adds to the several dozen post-AGB disk binaries with known orbital parameters. The orbital period falls on the short side of the period distribution of the other orbits.

Time-resolved spectroscopy allowed to detect gas streams in BD+46$^\circ$442, indicating that it is an interactive binary. H$\alpha$ (and to a smaller extent higher Balmer lines and the Na I D) are found to alternate between double-peaked emission, which is characteristic of a Keplerian disk, and a P Cyg-like profile, which is characteristic of an outflow. The blue absorption peaks up to 300 km s$^{-1}$ and develops only around the giant’s superior conjunction. We suggest it is due to a jet that originates in the accretion disk around the companion. In addition, strong metal lines display central or slightly blue-shifted absorption inside the photospheric profiles. Similar features are also observed in some massive interactive binaries and likely in several other post-AGB disk sources (like in the famous Red Rectangle).

The discovery of mass transfer and, possibly, accretion-driven jets in post-AGB binaries opens a new avenue to explore some of the long-standing puzzles of these objects, such as a variable mass-loss rate, a long lifetime of the circumstellar disks, a lack of extended dusty nebulae (Siódmiak et al. 2008, Lagadec et al. 2011), and the bipolar structure of the gaseous outflows (Bujarrabal et al. 2007). By uncovering more systems like this in the course of our spectroscopic survey, aided by complementary observations, we hope to pin-point the exact geometrical structures responsible for the various non-photospheric features. This will enable to construct realistic hydrodynamical models, providing a more solid basis for the theory of binary evolution.

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Appendix A: Representative line profiles

Fig. A.1 shows Hα and three other Balmer lines in BD+46°442 ordered according to the orbital phase, where each of the five orbital cycles (covering the first 1.5 years of observations) is designated with a different colour. A correlation with the orbital phase is obvious. The central absorption in Hα is not always aligned with the photospheric velocity, which means that the profile can not be represented by a simple superposition of a broad emission with a photospheric absorption. Near giant’s inferior conjunction (φ = 0.75) Hα exhibits a double-peak emission, while near superior conjunction (φ = 0.25) the blue peak is replaced with an extended blue absorption, as can also bee seen in the higher Balmer lines.

Fig. A.2 shows the behaviour of some metal lines and the CCF. The CCF represents the behaviour of the majority of the photospheric lines, that are symmetric and move with the orbital velocity. Low-excitation (λ < 6500 Å) lines, on the other hand, show additional circumstellar absorption. Near giant’s inferior conjunction (φ = 0.75) Hα exhibits a double-peak emission, while near superior conjunction (φ = 0.25) the blue peak is replaced with an extended blue absorption, as can also bee seen in the higher Balmer lines.
Fig. A.1. Balmer lines as a function of the RV phase ($\phi = 0$ corresponds to the maximum redshift). Different colours denote different orbital cycles. A solid vertical line marks our systemic velocity of $-98.9$ km s$^{-1}$, while dotted lines mark $50$ km s$^{-1}$ intervals from it. The arrows mark the photospheric velocity according to the CCF.
Fig. A.2. Same as in Fig A.1 only for the CCF and the representative metal lines of different strengths: Ca II 4d-4f doublet, Fe II (42) triplet, and the Na I D doublet. In each panel different line styles (solid, dashed, dotted) designate different members of the same multiplet.
Table A.1. Radial velocities of BD+46°442

| N | JD 2,455,000+ (d) | RV (km s\(^{-1}\)) | \(\sigma\) (km s\(^{-1}\)) |
|---|-------------------|---------------------|--------------------------|
| 1 | 31.71             | -89.62              | 0.26                     |
| 2 | 42.70             | -80.72              | 0.30                     |
| 3 | 60.70             | -75.28              | 0.33                     |
| 4 | 60.72             | -75.29              | 0.33                     |
| 5 | 85.64             | -92.73              | 0.27                     |
| 6 | 92.64             | -100.15             | 0.28                     |
| 7 | 100.62            | -109.71             | 0.28                     |
| 8 | 125.49            | -122.42             | 0.32                     |
| 9 | 131.53            | -120.76             | 0.30                     |
| 10| 156.40            | -102.56             | 0.26                     |
| 11| 159.55            | -100.60             | 0.26                     |
| 12| 159.56            | -100.42             | 0.27                     |
| 13| 199.33            | -75.91              | 0.30                     |
| 14| 216.38            | -83.05              | 0.29                     |
| 15| 224.36            | -90.37              | 0.29                     |
| 16| 421.63            | -116.87             | 0.30                     |
| 17| 425.67            | -112.94             | 0.30                     |
| 18| 432.59            | -106.89             | 0.27                     |
| 19| 468.66            | -78.39              | 0.30                     |
| 20| 471.62            | -76.86              | 0.32                     |
| 21| 499.54            | -83.24              | 0.26                     |
| 22| 507.47            | -91.20              | 0.27                     |
| 23| 533.48            | -123.07             | 0.27                     |
| 24| 573.34            | -107.14             | 0.25                     |
| 25| 581.34            | -100.30             | 0.22                     |
| 26| 767.71            | -76.56              | 0.30                     |
| 27| 769.71            | -77.36              | 0.30                     |
| 28| 776.73            | -80.47              | 0.29                     |
| 29| 783.69            | -85.43              | 0.27                     |
| 30| 791.74            | -94.47              | 0.25                     |
| 31| 797.73            | -101.45             | 0.26                     |
| 32| 826.65            | -123.22             | 0.28                     |
| 33| 835.57            | -121.05             | 0.29                     |
| 34| 841.50            | -118.54             | 0.28                     |
| 35| 842.59            | -117.29             | 0.30                     |
| 36| 845.61            | -114.46             | 0.29                     |
| 37| 848.41            | -112.60             | 0.28                     |
| 38| 852.52            | -109.55             | 0.25                     |
| 39| 857.64            | -104.90             | 0.26                     |
| 40| 860.60            | -102.75             | 0.25                     |
| 41| 866.54            | -98.31              | 0.25                     |
| 42| 870.56            | -95.45              | 0.25                     |
| 43| 872.61            | -92.87              | 0.24                     |
| 44| 880.56            | -84.86              | 0.26                     |
| 45| 882.46            | -83.74              | 0.26                     |
| 46| 884.55            | -82.57              | 0.27                     |
| 47| 886.49            | -81.61              | 0.26                     |
| 48| 888.55            | -80.62              | 0.25                     |
| 49| 890.52            | -79.87              | 0.25                     |
| 50| 890.54            | -79.79              | 0.25                     |
| 51| 903.38            | -74.61              | 0.25                     |
| 52| 911.41            | -77.25              | 0.28                     |
| 53| 934.41            | -96.74              | 0.30                     |
| 54| 940.36            | -105.17             | 0.31                     |
| 55| 943.44            | -108.88             | 0.30                     |
| 56| 948.40            | -114.77             | 0.28                     |
| 57| 953.36            | -118.43             | 0.27                     |
| 58| 956.40            | -119.74             | 0.26                     |
| 59| 957.48            | -120.08             | 0.26                     |
| 60| 968.45            | -121.61             | 0.33                     |

Notes. Radial velocities (barycentric correction included) measured with HERMES over the period July 2009 – February 2012.