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Abundance analysis of post-AGB stars

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Abstract. Using BD+46 442 as an example, we describe our analysis of the spectra of post-AGB stars (SpTs F-K, luminosity types I-II, [Fe/H]=-2.0...+0.5), obtained with the échelle spectrograph HERMES on the 1.2 m Mercator telescope. We obtain atmospheric parameters and atomic abundances using hydrogen line profiles and equivalent widths (EW) of weak metal lines. Our oscillator strengths and solar abundances for the majority of elements have been consistently adjusted to match the observed solar spectrum. The EW analysis is performed using F. Castelli's modified ATLAS9 photospheric models and C. Sneden's radiative transfer code MOOG. The resulting abundances are compared to those obtained by using the original R. Kurucz's ATLAS9 models and the WIDTH9 code. The outlined procedure can be employed for the spectroscopic analysis of the high-resolution spectra of warm (super-)giant stars in ground-based follow-up programs of Gaia.

1. Introduction

Since 2009 we perform a spectroscopic survey of various types of evolved stars with the échelle spectrograph HERMES on the Flemish 1.2 m Mercator telescope at La Palma [1]. The main goal is to obtain radial velocities for investigating binarity, but the large signal-to-noise ratio (S/N) spectra also allow us to carry out detailed studies of the photospheric parameters, including detailed abundance determinations. BD+46 442 is one of the first single-lined spectroscopic binaries (with an orbital period of 140 days) discovered in this survey [2]. It was selected based on its infra-red excess characteristic of discs around binary post-AGB stars [3]. The disc is believed to have formed when the primary was an AGB star and transferred its outer layers to the companion via Roche overflow or a wind accretion mechanism. The discs are apparently very stable as they are found around a large fraction of the post-AGB population [4]. Furthermore, many of these systems show an interstellar-like abundance pattern in their atmospheres, namely, refractory elements with high condensation temperatures ($T_{\rm cond}$), such as iron, that are deficient compared to the near-solar more volatile elements such as zinc [5], [6]. It can result from the gas-dust fractionation in the disc and the subsequent re-accretion of the depleted gas onto the star [7].

Post-AGB binaries have since long been proposed to be progenitors of symbiotic stars, chemically-peculiar giants and asymmetric planetary and proto-planetary nebulae. While imaging data is abundant thanks to the fast advances in space- and ground-based observations, the information on the orbital parameters and the evolutionary status of these systems is far from complete [8], [9]. Gaia will establish luminosities and provide first-order estimates of the temperature of Galactic post-AGB stars, which is sufficient to put a single star on an evolutionary track. But only through ground-based long-term high-resolution surveys, such as ours, will it

become possible to obtain information on binarity, metallicity, depletion, and nucleosynthesis in these stars. This information is essential for placing various groups of peculiar stars in the context of binary evolution.

In this contribution we outline a procedure for the chemical abundance determination of moderately metal-poor high-latitude F-G (super-)giants from high-resolution, large S/N optical spectra that can be employed in Gaia follow-up surveys. First, we briefly describe our spectral material, then the procedures for the determination of the basic photospheric parameters and chemical abundances, emphasizing deviations from local thermodynamical equilibrium (LTE) at low surface gravities. In Section 5 we evaluate the influence of the atmospheric model and the radiative transfer code on the computed abundance values.

2. Observations and data reduction

For the analysis we combined two HERMES exposures of BD+46 442 observed on the same night in August 2009 to obtain a S/N~130 spectrum. HERMES is a fiber-fed échelle spectrograph with an image slicer and an anti-fringe CCD coating. It provides a continuous coverage over λ =3800-9000 Å and a maximum spectral resolving power R~80 000. Two sets of bias, flat, and arc frames are obtained at dawn and at dusk, and the nearest one is used for the calibration of the science target. The typical uncertainty in the wavelength calibration is a few hundredths of an angstrom and is limited by the number of arc lines in a given spectral order. The precision of the radial velocity is ~0.2 km s⁻¹, limited by the instrument drift due to pressure fluctuations during the night. The data reduction is performed using a Python-based pipeline, while the radial velocity is determined via a cross-correlation method with a custom-made line mask (corresponding to a G2-type star in case of BD+46 442). More details on the instrument and software can be found in [10] and online at http://www.mercator.iac.es/.

3. Determination of the photospheric parameters and non-LTE effects

According to Simbad, BD+46 442 is an F2 III star. It provides an initial range of the effective temperature ($T_{\rm eff}$) from 6200 K to 8000 K. First, we attempted to use the line ratio method of Kovtyukh et al [11], [12] to determine $T_{\rm eff}$. We were however unable to identify any suitable pair of metal lines of their calibration method in our spectrum. The reason, as we explain below, is that most metals in BD+46 442 are depleted by a factor of five compared to the Sun. In addition, the lines are rather broad, with FWHM~25 km s⁻¹, which complicates the EW measurements.

We then turned to the hydrogen lines, which have the advantage over metal lines of being far less sensitive to metallicity and macro-broadening. In Fig. 1 we compare the H δ line to the synthetic profiles of [13] and the Paschen 14 line to the models of [14]. We find the best agreement for $T_{\rm eff}$ =6000–6500 K and log $g \leq 2$. The same result is obtained with H β , H γ , and Pa17 lines. The other hydrogen lines are too noisy or blended in our spectra, while H α could not be used due to contamination by circumstellar emission. Paschen lines are especially useful for eliminating large surface gravities; to obtain a satisfactory match with the models, however, we have to normalize the observed and the model profiles to pseudo-continuum regions between the lines, as the Paschen continuum flux is too high in the models. Both synthetic libraries [13], [14] are freely online available.

Next we performed an ionization balance analysis using Fe I and Fe II lines. We measured the EWs of metal lines using a line list with oscillator strengths $(\log(gf))$ from V. Kovtyukh (2010, personal comm.), which is a slightly updated version of the list published in [15]. To eliminate blends, we consulted with the interactive spectral atlases in SpectroWeb by A. Lobel [16], [17] online available at http://spectra.freeshell.org/spectroweb.html. To convert EWs to abundance values, we used the LTE radiative transfer code MOOG of C. Sneden, available

at http://www.as.utexas.edu/~chris/moog.html, and the ATLAS9 atmosphere models with the new opacity distribution functions of F. Castelli and R. Kurucz [18].

The typical behavior of iron lines with EW is shown in the left-hand panel of Fig. 2. The trend with EW can be removed by varying the value of the microturbulence velocity (V_{tur}) , while the difference between the average iron abundance from Fe I and Fe II lines can be eliminated by varying the log g-value. However, as shown in the right-hand panel, strong Fe I lines require lower V_{tur} - and log g-values compared to Fe II lines. In addition, a plot of the iron abundance value from Fe I and Fe II lines versus the excitation energy of the lower level (Fig. 3), reveals that low-excitation Fe I lines require a larger $T_{\rm eff}$ (>7000 K) incompatible with the Fe II and hydrogen lines. This is a known effect in yellow supergiants [15] and post-AGB stars [19]. It is usually explained by over-ionization in Fe I lines compared to the LTE case. The effect becomes more pronounced at higher temperatures, lower gravities, and lower metallicities (see Bergemann, this Volume). The recipe for the LTE calculations is therefore to utilize ionic lines such as Fe II, and the high-excitation/weak lines of neutral lines. Adopting $T_{\rm eff}$ =6250±250 K, and extrapolating the Fe I abundance values to EW=0, we obtain for BD+46 442 log g=1.5\pm0.5, V_{tur} =4.0±0.5 km s⁻¹, and [Fe/H]=-0.7\pm0.2 (Fig. 2), with lower/higher $T_{\rm eff}$ corresponding to lower/higher log g- and [Fe/H]-values.

4. Chemical composition

The abundance values of all 22 elements determined in this work are shown in the upper panel of Fig. 4 where the lines are ordered according the EW-values, and the elements according the $T_{\rm cond}$. The abundances are given relative to the solar values, or the adjusted photospheric abundances of [20] (see Section 5). We call this 2-D representation an 'abundogram', because it is a good diagnostic of non-LTE effects (such as the dependence of Fe I abundances on the EWvalues) and of a possible depletion with $T_{\rm cond}$ (that would be manifested by the color gradient in the vertical direction). Although we do not find strong non-LTE effects in other elements



Figure 1. The observed hydrogen line profiles of the post-AGB star BD+46 442 (in black) overlaid with model line profiles (in red) of [13] and [14]. H δ is shown for $R=80\,000$, while Pa14 for $R=20\,000$. Based on the comparison we estimate the effective temperature of BD+46 442 at 6250 ± 250 K and the surface gravity log g below 3.



Figure 2. The iron abundance as a function of equivalent width of Fe I (in blue) and Fe II (red) lines separately, computed with MOOG for two sets of photospheric parameters. The right-hand figure represents our best fit model because the Fe II abundances do not show a dependence on the EW (due to the correct microturbulence velocity) and also match the abundances of weak Fe I lines (due to the proper value of the surface gravity). The abundance values from strong Fe I lines deviate because they are affected by non-LTE effects at low surface gravity.



Figure 3. Iron abundance values from Fe I and Fe II lines as a function of the lower excitation potential (χ). This graph is often used to determine the effective temperature. However, Fe I lines show a trend with χ due to non-LTE effects. The Fe II lines, on the other hand, show no trend, confirming the validity of the T_{eff} -value obtained from the hydrogen lines.

(except perhaps for the well-known case of N I), they can be masked by the small number of lines. For obtaining an average abundance per ionization stage, we divided all species into three

groups: 1) ions that do not show a trend with EW, 2) neutrals for which at least three lines of $EW \leq 50 \text{ mÅ}$ are available, and 3) the remaining lines, and averaged them accordingly. The first group provides the most reliable abundance values, while the last group the least reliable.

The averaged abundances are represented in the lower panel of Fig. 4, where the symbol size signals the reliability of the abundance value. The error-bars represent the RMS of the average abundances. The plot reveals that the majority of metals are underabundant relative to the Sun by 0.7 - 1.2 dex. The more volatile elements such as C, S, and Na, on the other hand, show less underabundant values by ~0.3 dex. It could indicate a small depletion with $T_{\rm cond}$, a possible sign of contamination by material from the disc. On the other hand, a more plausible explanation for this pattern is that we measure the original composition of a thick disc star with enhanced abundances of α -process elements (Si, S, Mg, Ti). This is consistent with the low abundance of zinc, a metal with low $T_{\rm cond}$ [7] (although we have only one weak line for this element).

5. Comparison of ATLAS9 & Castelli, WIDTH9 & MOOG

Former studies, including those of Kovtyukh *et al*, employed an earlier version of the ATLAS9 atmosphere models and the LTE WIDTH9 code by R. Kurucz, available at http://wwwuser.oat.ts.astro.it/castelli/sources/width9.html. In particular, their $\log(gf)$ -values were adapted from the original values by forcing them to match the solar abundance values of [20] using EW-values they measured in the solar spectrum, and utilizing the canonical 5777 K/4.4/1.0 solar model of the earlier ATLAS grids. It may not be possible to re-calculate hundreds of objects that have been studied this way. A more practical approach is to evaluate the differences between their and our set of models and transfer codes, for both BD+46 442 and the Sun.

The result of the comparison for BD+46 442 is shown in Fig. 5. All abundances have been computed with the same line list, including the same oscillator strengths. In the left-hand panel we show the abundance line-by-line difference for the calculations with MOOG using two different atmosphere models: Castelli's (or 'ATLAS9 new', e.g., our adopted model) and the original ATLAS9 model. In the right-hand panel we show the combined difference in case both the atmosphere model and the transfer code differ from ours. The top row shows the difference for iron lines, while the bottom row for several other representative elements. From the comparison we find that the atmosphere model of Castelli yields systematically lower abundances by 0.07-0.11 dex, with the exception of nitrogen with a difference of -0.16 dex. The differences do not depend on the EW-values. On the other hand, using WIDTH9 instead of MOOG results in both negative and positive differences, but of a smaller amount: up to 0.03 dex, and the strong lines are more affected than the weak lines. Overall, the maximum uncertainty caused by the choice of the atmosphere model and transfer code is at most 0.15 dex for EW-values <170 mÅ. We perform a similar analysis for the Sun (the solar EWs are kindly provided by V. Kovtyukh) and obtain differences of the order of a few hundredths of a dex, mostly with negative sign, but which become positive for large EWs. These differences are still smaller in BD+46422 than both the RMS scatter of the line-to-line abundance of a given element, and the uncertainties due to those in the atmosphere model parameters. The RMS scatter, caused by the uncertainties in the line oscillator strengths and the measured EWs, constitutes 0.1–0.2 dex (Fig. 4), while uncertainties caused by the atmosphere model parameters amount to 0.1–0.3 dex (for $\Delta T_{\rm eff}$ =250 K, $\Delta \log$ g=0.5 dex, see 2).

6. Summary

We have analyzed a S/N~130, R~80,000 spectrum of a post-AGB F giant with a dusty disc; a single-lined spectroscopic binary. The Balmer and Paschen line profiles allow us to estimate the effective temperature of 6250 ± 250 K. The EWs of Fe I and Fe II lines enable us to simultaneously



Figure 4. The upper panel shows an 'abundogram', or a 2-D representation of the abundance values in BD+46 442. Each spectral line is represented with a dash symbol at the appropriate EW and the element condensation temperature. The colors code the abundance values compared to the Sun. The lower panel is a more common representation of the chemical composition that averages the abundances of individual lines. Only lines with EW \leq 170 mÅ are used in our analysis, and only lines with EW \leq 50 mÅ are used for averaging neutral species because of non-LTE effects in medium-strong lines. The size of the symbols is proportional to the quality of the abundance determination (larger dots show more accurate values). In the plots, BD+46 442 appears to be a slightly metal-poor star ([X/H] \sim -0.7) with enhanced abundances of the α -elements and without strong depletion of refractory elements characteristic for some post-AGB stars with discs.



Figure 5. The two panels show the difference in abundances for BD+46 442 by computing abundances using the same line list and the same photospheric parameters but 1) different versions of the atmosphere model (left-hand panel) and 2) different atmosphere models and different transfer codes (right-hand panel). The comparison is shown for the iron lines and for a number of other representative elements. F. Castelli's atmosphere models result in systematically smaller abundances of ~0.1 dex compared to the original ATLAS9 models. The differences can decrease or increase by ~0.03 dex for a given element/ion and EW using WIDTH9 instead of MOOG. These differences are still smaller compared to errors due to uncertainties in the model parameters $T_{\rm eff}$ and log g. Similar effects, but to a smaller degree, are also observed in the Sun.

constrain the surface gravity of log $q=1.5\pm0.5$, [Fe/H]= -0.7 ± 0.2 dex, and the microturbulence velocity of $V_{tur}=4.0\pm0.5$ km s⁻¹. We determine the abundance values of 22 elements in total. For Ti, Cr, and Fe these values are obtained from two ionization stages. Lines with $EW \leq 170 \text{ m}\text{\AA}$ are used for the ions, while EW < 50 mÅ for the neutrals. The dominant source of the abundance errors is the uncertainty in the effective temperature and surface gravity, followed by the uncertainty in the EW measurements and the employed oscillator strengths. Our analysis of Fe I lines confirms an urgent need for non-LTE corrections exceeding 0.2 dex to analyze lines with EW>50 mÅ. We also compare two radiative transfer LTE codes (MOOG and WIDTH9) and two versions of ATLAS9 atmosphere models. Hence, we detect maximum differences of 0.15 dex for N I lines. The errors caused by different models are generally larger than for different transfer codes, but they depend less on the measured EW-values. Despite all these uncertainties, our method (which was originally developed for massive supergiants) is adequate for detecting the metal-poor nature of post-AGB stars and to distinguish it from chemical depletion effects. Considering possible non-LTE effects in these stars, we propose a new 2-D representation of abundance values with EW and e.g., $T_{\rm cond}$ or atomic number. We call this 2-D abundance diagram an *abundogram*, complementing the traditional 1-D diagram of average abundance values. The outlined method can be employed for abundance determinations in low-gravity F-and G-stars with solar and sub-solar metallicity that will be observed in future ground-based surveys in support of the Gaia mission.

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