Multiepoch Optical Spectroscopy of the Post-AGB Star HD 161796

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Abstract

The evolutionary rate of the pulsating post–asymptotic giant branch (post-AGB) star HD 161796 was suspected to be high. Spectra of HD 161796 acquired during a time span of 18 yr are analyzed with the main goal of determining the evolutionary increase in temperature and comparing it with the latest post-AGB star evolutionary models. Inspection of the spectra reveals splitting and significant temporal variation in strong absorption lines, suggesting the presence of shock waves in the atmosphere of the pulsating star. The Hα profiles point to variable incipient mass loss. Most medium-strength lines have variable blue wings, while the red wings remain stationary, presumably due to variations in the warm outflow from the stellar surface. The modeling of the spectra suggests the average value for the effective temperature to be 7275 K, and for surface gravity, a value of log g = 0.7. Different iron abundances are found for different spectra, probably due to the inability to model the pulsating photosphere with stationary atmospheric models. On average, we arrive at [Fe/H] = −0.06. The observed underabundance in neutron capture and some other elements is inferred to be a consequence of dust–gas separation. It is confirmed that, during pulsation, the stellar surface is hotter when the star is smaller in size. The spectra show a 420 K range in effective temperature—a smaller variation than can be found from pulsation-related changes in color. No significant rate of evolution is seen, contrary to earlier suggestions. The initial mass of the star is evaluated to be $$\lesssim 2 M_\odot$$.

Unified Astronomy Thesaurus concepts: Post-asymptotic giant branch stars (2121); UU Herculis stars (1754); Stellar atmospheres (1584); Late stellar evolution (911); Stellar pulsations (1625); Stellar abundances (832)

1. Introduction

The post-asymptotic giant branch (post-AGB) phase is rapid and one of the poorly understood phases of evolution for low- and intermediate-mass stars (with initial masses from ~0.8 to 8 $$M_\odot$$). In the preceding AGB stage, the star loses considerable amounts of mass via the stellar wind. When most of the outer layers have been removed, the star enters the post-AGB phase, where at almost constant luminosity it increases surface temperature. At one point, the temperature is high enough for stellar photons to ionize previously shed-off matter, creating a planetary nebula (PNe; Van Winckel 2003). The rate at which a post-AGB star increases its temperature impacts the formation and detectability of the subsequent PNe, and depends mainly on the mass of the star (Miller Bertolami 2016). It is known that significant changes in the nature of the stellar wind occur near the transition between the AGB and post-AGB stages, as the isotropic wind tends to transform into an aspherical outflow (Balick & Frank 2002). For the former stage, the winds are more or less understood (Höfner & Olofsson 2018), but there is little knowledge of them in the latter.

The post-AGB star HD 161796 (IRAS 17436+5003) belongs to a historical class of UU Herculis–type stars (Sasselov 1984), whose high luminosity and large height above the galactic plane, as well as other characteristics, posed a question about the mass and evolutionary status of these objects. It was unclear whether they were young, massive Population I stars or old, low-mass Population II stars. Most of these stars have turned out to be of low mass, and in the case of HD 161796, the best evidence for such a scenario came from the discovery of infrared excess, suggesting AGB mass loss (Parthasarathy & Pottasch 1986), and a CNO abundance pattern, which is atypical for Population I supergiants (Luck et al. 1990).

Initial attempts to derive the effective temperature for HD 161796 using photometric calibrations yielded a value around 6400 K (Fernie 1983; Fernie & Garrison 1984), which was estimated to be as much as 100 K less than the F3Ib spectral class (Bidelman 1951; Fernie & Garrison 1984) would suggest. The analysis of the UV spectrum by Parthasarathy et al. (1988) gave similar results for both the effective temperature and spectral classification. Mantegazza et al. (1989) proposed the assumption of large circumstellar reddening, thereby solving the problem. Mid-infrared imaging (Gledhill & Yates 2003) and polarimetric imaging (Min et al. 2013), in combination with spectral energy distribution (SED) modeling, in which circumstellar extinction was taken into account, resulted in a central star with a 7250–7500 K temperature.

Analyses of high-resolution spectra have resulted in $$T_{\text{eff}} \sim 7150$$ K (Klochkova et al. 2002; Kipper 2007; Takeda et al. 2007; Luck 2014), but Luck et al. (1990) arrived at $$T_{\text{eff}} = 6600$$ K. All of these studies resulted in [Fe/H] ~ −0.3 dex, with the exception of Luck (2014), who derived [Fe/H] = −0.09. The values for log g from these studies range from 0 to 1.1 dex. The fact that the earliest of the high-resolution spectra studies resulted in lower $$T_{\text{eff}}$$, as well as the confident classification by Suárez et al. (2006) of the star being of A7I type, and therefore hotter than the previous estimates, suggests that the star might be evolving at a rapid rate. In fact, Klochkova et al. (2002) reported an evolutionary rate of at least 50 K per year for HD 161796, based on their results and those of Luck et al. (1990) and Klochkova & Panchuk (1988).

Although nowadays it is clear that HD 161796 is in the post-AGB stage, questions about its precise mass remain. Staśnśka et al. (2006) compared the star’s position in the $$T_{\text{eff}}$$–log g plane with theoretical evolutionary tracks by Blöcker (1995), and

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estimated it to have a current mass of at least $0.6 \, M_\odot$, suggesting an initial (main-sequence) mass of no less than $3 \, M_\odot$. In a similar manner, and backed up by other considerations, Kipper (2007) favored a current mass of $0.84-0.94 \, M_\odot$ ($5-7 \, M_\odot$ on the main sequence). On the contrary, Gledhill & Yates (2003) have estimated the star as having an initial mass of $1-2 \, M_\odot$.

The peculiar pulsation properties of HD 161796 were pointed out by Fernie (1983), when he noticed that the star pulsates with different periods at different times, and concluded that it was switching between different pulsation modes. Based on long-term light and radial velocity observations, it has been shown that multiple modes of pulsation exist simultaneously and, indeed, that significant changes in pulsation period do occur (Hrivnak et al. 2015, 2018). The variability in V is of low amplitude ($\lesssim0.21^m$, peak-to-peak), with a dominant period of 45 days, over a 35 yr observation interval. No evidence for binarity is found (Hrivnak et al. 2017). Hasanova et al. (2014) studied the variations of the H$\alpha$ and Na D lines, and showed that they are connected to the stellar pulsation. The variation of the H$\alpha$ profile, the near-infrared (NIR) Ca II triplet, and some low-excitation metal lines have been noted by Van de Steene et al. (2018).

In this study, we investigate temporal changes in the optical spectrum and atmospheric parameters of HD 161796 by analyzing multiple high-resolution spectra acquired over 18 yr. The goal is to determine the evolutionary rate and compare it with the latest post-AGB evolutionary models. Additionally, we calculate photospheric abundances for a large number of chemical elements. The observed spectra are described in Section 2. A description of the features and variations visible in the spectra is given in Section 3.1. The determination of the atmospheric parameters for each of the spectra is described in Section 3.2. The derivation of photospheric abundances is presented in Section 3.3. The results are discussed in Section 4 and then summarized in Section 5.

2. Observations

We have collected spectra of HD 161796 acquired during the last 18 yr with four different instruments. The earliest data for 2003 and 2004 have been retrieved from the ELODIE archive. The polarimetric spectra observed with ESPaDOnS at CFHT in 2005 and 2009 have been taken from the CFHT Science Archive. Both of the ESPaDOnS spectra consist of eight individual exposures at different polarization. No changes were observed between the individual exposures, so they were summed together. For 2011 and 2013, we use spectra that we observed on multiple nights with the coudé échelle spectrograph MAESTRO mounted on the 2 m telescope at Peak Terskol Observatory. Finally, we observed one spectrum in 2017 and two spectra in 2021 at Moletai Astronomical Observatory with the spectrograph VUES. The specific dates, average signal-to-noise ratios (S/N), and heliocentric radial velocities are shown in Table 1.

The radial velocities are measured using a large number of weak and medium-strength absorption lines by cross-correlating the symmetric central parts of the profiles with their mirror profiles (see Section 3.2 for the justification of this method). For all of the spectra, the statistical error for radial velocity is no larger than $0.2 \, \text{km s}^{-1}$. By inspecting the telluric lines for zero-point shift of the radial velocity scale, we estimate that the systemic error due to it is no larger than $0.3 \, \text{km s}^{-1}$. The widths of the telluric lines suggest spectral resolutions of $R = \lambda/\Delta\lambda \sim 35,000, 55,000, 31,000$, and $34,000$ for the ELODIE, ESPaDOnS, MAESTRO, and VUES spectra, respectively.

For the MAESTRO spectra, a standard procedure of bias subtraction, flat-field division, scattered-light subtraction, order extraction, and wavelength calibration was done. The VUES spectra were reduced by using the automated pipeline described in Jurgenson et al. (2016). The ESPaDOnS spectra from the CFHT Science Archive were retrieved having already been reduced using the Libre-ESpRIT package (Donati et al. 1997). The ELODIE archive spectra were also retrieved having already been reduced, and notes about the reduction process can be found in Mouttaka et al. (2004). The ELODIE spectra extend only up to $6800 \AA$. For all of the spectra, the continua were normalized by dividing them with a spline fitted to interactively placed continuum points. The continuum normalization, the measurement of the radial velocities and equivalent widths, and the MAESTRO spectra reduction were done using DECH software.

3. Analysis of Spectra

3.1. Visual Inspection

By comparing the spectra observed at different epochs, we notice significant variation in the profiles of the strong absorption lines. Some examples are shown in Figure 1. The H$\alpha$ profile consists of a variable narrow central absorption dip that is superposed on a normal broad absorption without any significant variation. The central dip appears to have variable emission components that can be seen in blue, red, or both sides of it. The central absorption and emission components appear to change both in position and intensity. Also, changes in the width and overall shape of the central absorption are evident. The spectra obtained in 2011 November show that significant variation can be observed on a timescale of a few days/weeks.

The Na D lines also are subject to variability. Changes are seen in the central photospheric component as well as in the blue wing. However, the circumstellar and interstellar components as identified by Kipper (2007) seem to be stationary in the radial velocity scale. These lines are better resolved by our high-resolution ESPaDOnS spectra, and, according to them, the circumstellar component has a heliocentric radial velocity of $-68.3 \, \text{km s}^{-1}$. A similar velocity of $-68.1 \, \text{km s}^{-1}$ ($-14 \, \text{km s}^{-1}$)

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Table 1

| Spectrograph | Date     | MJD      | S/N | $V_r$ (km s$^{-1}$) |
|--------------|----------|----------|-----|---------------------|
| ELODIE       | 26/3/2003| 52,724.06| 175 | -51.6               |
| ELODIE       | 19/8/2004| 53,236.82| 160 | -52.3               |
| ESPaDOnS     | 22/8/2005| 53,604.29| 420 | -54.0               |
| ESPaDOnS     | 16/2/2009| 54,878.64| 685 | -53.4               |
| MAESTRO      | 14/11/2011| 55,879.89| 90  | -51.6               |
| MAESTRO      | 19/11/2011| 55,884.84| 140 | -49.2               |
| MAESTRO      | 21/11/2011| 55,886.85| 85  | -49.8               |
| MAESTRO      | 22/11/2011| 55,887.81| 115 | -49.8               |
| MAESTRO      | 7/3/2013  | 56,358.15| 130 | -54.3               |
| MAESTRO      | 8/3/2013  | 56,359.20| 100 | -53.9               |
| VUES         | 17/3/2013 | 57,829.12| 65  | -55.6               |
| VUES         | 23/3/2021 | 59,296.07| 45  | -52.8               |
| VUES         | 1/5/2021  | 59,335.89| 50  | -51.9               |


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\[ R = \lambda/\Delta\lambda \sim 35,000, 55,000, 31,000, \text{and} \, 34,000 \]
Figure 1. The variation of the intense spectral lines. The spectra from 2003, 2004, 2005, and 2009 are shifted upward by 1 in relative flux, and are depicted with the blue, cyan, gray, and black lines, respectively. The spectra from 2011 and 2013 are shifted by 0.5. The spectra from 2011 November 14, 19, 21, and 22 correspond to the yellow, light green, green, and dark green lines, respectively. The spectra from March 7 and 8 are shown in orange and brown. The 2017, 2021 March, and 2021 May spectra are colored in pink, purple, and magenta, respectively. Na D2 and CaII 8542.09 Å have approximately the same velocities as in the case of the 2011 and 2013 spectra; however, the stationary components seem to be shifted toward blue by around 6–7 km s\(^{-1}\). Both the D1 and D2 lines have similar profiles.

The 8542.09 Å profile of the calcium IR triplet is split into two components that appear to be stationary at around −36 and −63 km \(s^{-1}\) in radial velocity in the 2009, 2011, and 2013 spectra; however, in the 2005 spectrum, no pronounced red component is seen, and the whole profile seems to be shifted toward blue by around 6–7 km s\(^{-1}\). The same shift of the 2005 profile relative to the other spectra, as well as multiple components, are also seen in the other two lines of the triplet. Unfortunately, the regions around these two lines are affected by gaps between spectral orders in the 2011 and 2013 spectra; however, the stationary components seem to have approximately the same velocities as in the case of the 8542.09 Å line. The shape of the 8498.023 Å profile in 2005 suggests the presence of at least three components, one of which resides at −63 km \(s^{-1}\). The value of −63 km \(s^{-1}\) is close to the one linked with the expansion velocity of 8.6 km \(s^{-1}\) \((V_{\text{helio}} - V_{\text{exp}} = -62.7 \text{ km s}^{-1})\) as derived by He et al. (2014). The uncertain continuum normalization and low S/N make analysis of the lines of the CaIR triplet in both the 2011 and 2021 spectra difficult.

Variation is also seen in other strong metal lines. In the Fe II 5169.03 Å line, two absorption components are clearly distinguishable in some epochs. The same behavior is observable in the Fe II 5018.44 Å line. Significant variations in the shapes of the profiles are visible in Ti II 4571.97 Å and a few other lines, e.g., Sc II 4246.82 Å, Ti II 4501.28 Å, Fe II 4923.92 Å, and the O I 777 nm triplet.

Most of the medium-strength lines exhibit variability in their central depths and blue wings, while the red wings remain almost stationary and unchanged. To better investigate this, we summed the spectra obtained on 2011 November 19, 21, and 22 to increase the average S/N to ~195. The same was done for the spectra acquired on 2013 March 7 and 8, to yield an average S/N of ~155. It should be noted that we observe small night-to-night variation in line depths when inspecting the 2011 November and 2013 March spectra; however, we believe that this is due to small changes in the slit width during observation. An example of the medium-strength line variation around 5423 Å is shown in Figure 2. The lines appear to be broadest in 2011, and extended blue wings are prominent. The opposite is seen in 2009—the lines are narrow and there seems to be a lack of absorption in the blue wings. For a very few lines in the 2009 spectrum, emission is seen in the blue wings, resembling inverse P Cygni-type profiles. A comparison of the two highest-signal spectra (2005 and 2009) reveals that similar variability can also be seen in weak lines. This variation is seen for both atomic and ionic lines, and for both low- and high-excitation lines of different chemical elements. We leave a more detailed analysis of spectral-line variation to a future paper.

3.2. Homogeneous Derivation of Photospheric Parameters

We analyzed all of the spectra in a homogeneous way by using the same spectral lines and following the same approach to fit the lines and derive photospheric parameters. We measure the equivalent width (EW) by fitting a Gaussian to the symmetric central part of the profile, since it provides the only consistent way of measuring the EWs in all of the spectra without including variable blue-wing features that static 1D atmosphere models are not able to describe. We find that, on average, temporal variation of up to ~40% is seen in the EWs. We notice a trend for the FWHM of lines to increase with their intensity, which cannot be explained by macroturbulent broadening–induced line profile changes. This tendency is seen for all of the spectra. To confirm our EW measurements, we compare our results for 2003 with those of Luck (2014), since he used the same spectrum (Figure 3). The overall agreement is satisfactory; however, it can be seen that we obtain slightly lower values, presumably due to our method of fitting the lines. Since not all lines are seen in every spectrum, due to spectral coverage, gaps between orders, or too-low S/N, we use...
a limited number of iron lines to derive photospheric parameters—in the wavelength range from 4007 to 6678 Å, we measure EWs for 127 Fe I and 47 Fe II lines. An exception is the VUES EWs for 127 Fe I and 47 Fe II lines. An exception is the VUES spectra, where, due to the significantly lower signal, we use up to 20 fewer lines.

From the measured EWs, we calculate photospheric abundances using the stellar spectral synthesis code SPECTRUM (Gray & Corbally 1994). Model atmospheres are taken from the ATLAS grid (Kurucz 2005) and interpolated using the code iSpec (Blanco-Cuaresma et al. 2014). Atomic data is taken from VALD (Piskunov et al. 1995; Kupka et al. 1999).

We notice that the standard procedure of determining photospheric parameters, based on the excitation and ionization equilibria of iron line abundances, is not satisfactory, since Fe I and Fe II lines give different values for both microturbulent velocity and effective temperature (Figure 4). For HD 161796, an issue with the microturbulent velocity has already been reported by Klochkova & Panchuk (1988) and Kipper (2007). The former study arrived at 3.2 and 7 km s$^{-1}$ by Klochkova & Panchuk 1988, and the latter at $-4.5$ and 6.5 km s$^{-1}$ for the Fe I and Fe II lines, respectively. In our case, the microturbulent velocity from Fe I is approximately 1 km s$^{-1}$ lower than that derived from the Fe II lines. A solution to this problem in the case of intermediate-mass supergiants has been proposed by Kovtyukh & Andrievsky (1999). According to them, the inconsistency is caused by nonlocal thermodynamic equilibrium (non-LTE) effects on Fe I lines; therefore, Fe II lines should be used for the determination of the microturbulent velocity, since they are not significantly affected by non-LTE in F supergiants (Lyubimkov & Boyarchuk 1983; Boyarchuk et al. 1985). We believe that non-LTE effects are also responsible for the inconsistencies in the log $\varepsilon$-lower excitation potential (LEP) trends, since non-LTE abundance corrections tend to be more positive for low-excitation lines (see, e.g., Mashonkina et al. 2011).

We derive the microturbulent velocity and surface gravity following the prescription of Kovtyukh & Andrievsky (1999). Fe II lines are used for the microturbulence determination in the standard way. For Fe I abundance, we use the extrapolated value where the trend in the log $\varepsilon$-EW plot intercepts the $y$-axis (EW = 0 mÅ). This value is used for the surface gravity determination from the ionization equilibrium. $T_{\text{eff}}$ is determined by using Fe II lines. If we were to use Fe I lines instead, then we would arrive at a temperature 600–700 K higher. The uncertainties for effective temperature and microturbulence are $1\sigma$ errors for slope coefficients in abundance trends with LEP and EW. The uncertainty for surface gravity corresponds to a 0.1 dex change in difference between Fe I and Fe II abundances.

The results for each epoch are shown in Table 2. We see different values for $T_{\text{eff}}$, ranging from 7080 to 7500 K; for log $g$, ranging from 0.5 to 1.0 dex; and for $V_{\text{mic}}$, ranging from 4.3 to 5.5 km s$^{-1}$, with the average values being 7275 K, 0.7 dex, and 4.8 km s$^{-1}$. Different photospheric parameters for different spectra are expected, since the star is variable. Nevertheless, no variation is expected for the iron abundance, for which we see log $\varepsilon$(Fe) values ranging from 7.3 to 7.5 dex, with an average of 7.44 dex. This is probably due to the inability to correctly model the pulsating photosphere of the star with stationary model atmospheres.

3.3. Abundance Derivation

For a detailed abundance analysis, we choose the 2009 spectrum, since it has the highest S/N and R, as well as large undisturbed wavelength coverage. The approach for deriving photospheric parameters and iron abundance is the same as in Section 3.2. Abundances for other elements are derived by simply averaging the values for the individual lines of the specific species. To arrive at more precise photospheric parameters, we employ more iron lines spanning a larger wavelength range.
Ultimately, using 286 FeI and 117 FeII lines, we derive $T_{\text{eff}} = 7230 \pm 50$ K, $\log g = 0.53 \pm 0.11$, and $V_{\text{mic}} = 4.0 \pm 0.4$ km s$^{-1}$ (Figure 4). By comparing the results for the 2009 spectrum using the limited-line list and the full one, we see that there is good agreement between the two.

In total, we derive abundances for 35 different atomic and ionic species in the wavelength range of 3756–9051 Å. No lines stronger than 200 m Å are used, and the average EW is 30 m Å. The abundances and their uncertainties are shown in Table 3. The uncertainty $\Delta$ for every abundance is calculated using the following equation:

$$\Delta = \sqrt{\left(\frac{\sigma}{N}\right)^2 + \left(\Delta_{T_{\text{eff}}}\right)^2 + \left(\Delta_{\log g}\right)^2 + \left(\Delta_{V_{\text{mic}}}\right)^2},$$

where the statistical standard error due to the line-to-line spread in abundances is denoted by $\sigma$, $\Delta_{T_{\text{eff}}}$, $\Delta_{\log g}$, and $\Delta_{V_{\text{mic}}}$ correspond to changes in abundances induced by varying photospheric parameters by their uncertainties. On average, the values for the temperature-, gravity-, and microturbulence-related abundance uncertainties are 0.05, 0.04, and 0.01 dex, respectively.

We notice that the Fe abundances derived from the red and NIR part of the spectrum are 0.1 dex lower than those derived from shorter wavelengths. In fact, this wavelength dependence is also seen in the analysis of a limited number of Fe lines in Section 3.2. Although the reason for this is unclear, we do not expect that it will significantly impact our results for abundances. For iron, no more than 30% of the lines are measured in red or longer wavelengths. This is probably the most significant contribution to the 0.04 dex difference in iron abundance between the results of the limited line list and the full one. It is hard to definitely conclude the presence of this effect for other elements, due to the lower number of measured lines. If it is present, then nitrogen would be the most affected and its abundance would be underestimated by $\sim 0.1$ dex, since all of the measured lines lie in red or longer wavelengths.

Compared to most of the previous studies, we arrive at an iron abundance that is 0.2 dex higher. It is hard to explain such a discrepancy. Partially, at least, this could be attributed to the different approach to deriving atmospheric parameters and iron abundance, as well as the quasi-stationary approach to modeling the pulsating atmosphere of the star. Better agreement with the iron abundance from the 2003 spectrum is found with the study of Luck (2014), in which the same spectrum was used.

For the first time, abundances are derived for gadolinium and potassium in the photosphere of HD 161796. For the latter, we use 7665 and 7699 Å lines, and overabundance ([K/H] = 0.56) is seen. No telluric lines seem to significantly blend them, and we see no indication of interstellar or circumstellar contamination. According to Reggiani et al. (2019), large negative non-LTE corrections can be expected for these lines. For all of the neutron-capture elements, we find similar underabundances—[n/H] $\sim -0.65$.

It should be noted that we see a tendency for the abundances derived from ionic lines to be higher than those derived from atomic lines. In all cases, the difference between the two abundance values is small—within the estimated uncertainties. Magnesium is an exception, with a difference of 0.23 dex between the abundances; however, we believe this discrepancy to be a result of the small number of lines used.

We stress that it is an open question as to which pulsation phase should be used in abundance analysis for post-AGB stars. Vasilyev et al. (2018) studied the validity of a quasi-static approach in spectroscopic analysis for Cepheid variables. Their analysis showed that photometric phases $\phi \approx 0.3–0.65$ (where $\phi = 0$ corresponds to the light maximum) give the most accurate results. For Cepheids, these pulsation phases correspond to the maximum expansion and early contraction stages. The different pulsation nature of lower-mass, post-AGB stars like HD 161796 (Hrivnak et al. 2018), the complexity of the light curve, and the lack of good time agreement between our data and photometric monitoring restricts us from ascribing reliable pulsation phases to our spectra. The only minor consolation, if it can even be considered as one, regarding the validity of our abundance analysis is the fact that we are using a spectrum that gives an iron abundance (for a homogeneous, limited line list) that is close to the average from all of the spectra.
### Table 3
Phospheric Abundances and Their Uncertainties

| Ion    | N  | log ε | σ  | Δ   | [X/H] | Ion    | N  | log ε | σ  | Δ   | [X/H] |
|--------|----|-------|----|-----|-------|--------|----|-------|----|-----|-------|
| C I    | 50 | 8.54  | 0.11| 0.06| 0.11  | Cr I   | 19 | 5.49  | 0.13| 0.10| −0.15 |
| N I    | 10 | 8.52  | 0.18| 0.07| 0.11  | Cr II  | 36 | 5.60  | 0.11| 0.04| −0.04 |
| O I    | 12 | 9.00  | 0.12| 0.04| 0.31  | Mn I   | 7  | 5.25  | 0.10| 0.10| −0.18 |
| Mg I   | 5  | 7.71  | 0.11| 0.10| −0.12 | Fe I   | 286| 7.40  | 0.16| 0.09| −0.10 |
| Si I   | 28 | 7.72  | 0.15| 0.08| 0.21  | Co I   | 4  | 4.75  | 0.17| 0.13| −0.24 |
| S I    | 13 | 7.42  | 0.11| 0.08| 0.30  | Ni I   | 47 | 6.08  | 0.10| 0.10| −0.14 |
| K I    | 2  | 5.59  | 0.08| 0.12| 0.56  | Zn I   | 2  | 4.34  | 0.01| 0.09| −0.23 |
| Ca I   | 21 | 6.07  | 0.08| 0.11| −0.27 | Zr II  | 7  | 1.85  | 0.04| 0.04| −0.73 |
| Ca II  | 2  | 6.12  | 0.01| 0.03| −0.22 | La II  | 6  | 0.42  | 0.12| 0.10| −0.68 |
| Sc II  | 7  | 2.46  | 0.14| 0.07| −0.69 | Ce II  | 7  | 0.85  | 0.12| 0.10| −0.73 |
| Ti I   | 6  | 4.42  | 0.23| 0.13| −0.53 | Nd II  | 5  | 0.89  | 0.23| 0.14| −0.54 |
| Ti II  | 31 | 4.47  | 0.20| 0.05| −0.48 | Sm II  | 4  | 0.42  | 0.15| 0.11| −0.54 |
| V I    | 1  | 3.71  | 0.20| 0.22| −0.22 | Gd II  | 2  | 0.41  | 0.29| 0.21| −0.66 |
| V II   | 11 | 3.76  | 0.12| 0.05| −0.17 |       |     |       |    |     |       |

Note. The abundances for the 2009 spectrum with the atmospheric parameters $T_{\text{eff}} = 7230 \pm 50$ K, log $g = 0.53 \pm 0.11$, and $V_{\text{mac}} = 4.0 \pm 0.4 \text{ km s}^{-1}$. Asplund et al. (2009) abundances are used as a reference for solar values. For species where only one line was measured, $\sigma$ is assumed to be 0.2 dex.

### 4. Discussion

#### 4.1. Shocks and Warm Outflow

Visual inspection of the spectra has revealed previously unknown variability in spectral features for HD 161796—most medium-strength lines are variable in the blue wings and central depths, while the red wings seem to remain almost unchanged. This variation seems to be independent of the element, ionization, and LEP of the species, and points to possible changes in the motion of warm gas near the surface of the star. The extended blue-wing phases correspond to outward motion and phases where there seems to be a lack of absorption in the blue wing, and the appearance of a few inverse P Cygni lines like those seen in HD 161796 suggest that matter is falling onto the star. This conclusion is corroborated by the shape of the Hα profiles that are typical for F supergiant post-AGB stars, irrespective of nebular morphology, as observed by Sánchez Contreras et al. (2008). It is suggested that Hα profiles like those seen in HD 161796 are a superposition of photospheric absorption and an emission component that originates in close stellar surroundings and indicates incipient post-AGB mass loss. The likely mechanism for producing the emission is shocks that either originate in the photosphere or result from the interaction between slow AGB and fast post-AGB winds. In the case of HD 161796, the variable emission component points to variable mass loss. The splitting and significant changes that we observe in the intense metal-line profiles suggest the presence of shock waves in the outer atmosphere of the star (Lèbre et al. 1996; Začs et al. 2016). Van de Steene et al. (2018) noted that in HD 161796 the red emission component of Hα is generally weaker than the blue one, which seems to be consistent with our spectra. The tendency for the emission “hump” in HD 161796–like Hα profiles to be displaced blueward from the narrow absorption feature was interpreted by Sánchez Contreras et al. (2008) as being related to the occultation of the receding part of outflowing stellar material by the central star. In such a case, the height above the photosphere of the Hα-emitting region should be comparable to the stellar radius. The seeming proximity of the Hα emission to the photosphere and the observed significant variation of the profiles over a timescale of a few days/weeks make atmospheric shocks the most likely source of exciting hydrogen gas. More high-resolution and high-S/N spectra are necessary to confirm our conclusions; however, if they are true, time-resolved spectroscopy of HD 161796 could prove useful in the study of the mass-loss mechanism in the post-AGB phase. Recently, binary interactions have been thought of as the main driver for the shaping of asymmetrical PNe from spherically symmetric AGB wind. For HD 161796, both symmetrical AGB and asymmetrical post-AGB winds have been observed (Ueta 2004), but there is no evidence for binarity (Hrivnak et al. 2017).

#### 4.2. Chemical Depletion

Takeda et al. (2007) did a non-LTE abundance analysis for several elements and, based on the [Zn/Fe] ratio, showed that the atmosphere of HD 161796 has suffered from chemical element depletion. By using their non-LTE abundance correction average values for S (−0.13) and Zn (0.21), and our derived abundances from the best spectrum in terms of signal, spectral resolution, and wavelength coverage, we arrive at [Zn/Fe] = 0.48 and [S/Fe] = 0.66. This places HD 161796 in between mildly depleted and nondepleted objects, according to Gezer et al. (2015). The average non-LTE corrections for C, N, and O (excluding the 777 nm O triplet), according to Takeda et al. (2007), are −0.11, −0.46, and −0.10. By plotting our abundances as a function of dust condensation temperature (Figure 5), we show that the underabundances for the Cu, Al, and neutron-capture elements and some iron peak elements are well described as being a consequence of depletion. We believe that depletion is caused by dust–gas separation, rather than the stellar wind preferentially picking up ions over atoms (see Giridhar 2020 for a short review). This is corroborated by the fact that for elements with low first ionization potential (FIP), significant underabundances should be observed in the latter case. Na and K are such elements, with respective values of
where $G$ is the gravitational constant, $\sigma$ is the Stefan–Boltzmann constant, and $M$ is the current mass of the star. By using minimum and maximum values for $T_{\text{eff}}$ and $\log g$ (corresponding to the 2011 and 2017 spectra), we estimate that the luminosity during pulsation varies by an amplitude of at least 40% around the average value. Luminosity is highest when the star is at its lowest temperature and surface gravity phase, and vice versa. This conclusion seems to be at odds with the photometric and radial velocity monitoring results for the phasing of the size and temperature variations of the star. Additionally, such a variation in luminosity corresponds to changes in brightness by $\sim 1^m$, while photometric observations show a maximum difference no larger than around $0.3^m$ in V-band magnitudes (Hrivnak et al. 2015, 2018). This points to the changes in surface gravity during pulsation being more subtle than we estimate, and suggests that we have not fully overcome the problems with photospheric parameter determination as described in Section 3.2.

4.4. Evolutionary Rate and Initial Mass

The photospheric parameters for each of the spectra are derived in a homogeneous way—the same line list and the same approach is used. Although, due to the relatively large pulsation amplitude for $T_{\text{eff}}$, we do not arrive at a very precise value for the evolutionary temperature increase, it is certainly not as fast as previously thought (Figure 6). Formally, we derive a rate of $5 \pm 6$ K per year. This points to the star having a low mass. The calculations of Oomen et al. (2019) showed that stars that suffer from depletion are expected to have prolonged lifetimes. They estimate that the post-AGB phase may even be five times longer than that of a normal, undepleted star. However, this was modeled in a scenario involving the reaccretion of gas from the circumstellar disk, and is probably not directly applicable to HD 161796. Additionally, the depletion pattern that we observe is not pronounced; therefore, we believe that such evolution-prolonging effects are not important in the case of HD 161796, and do not affect our conclusions about the mass of the star.

A comparison of the average effective temperature and surface gravity values that we derive ($T_{\text{eff}} = 7275$ K and $\log g = 0.7$) with the values predicted by the post-AGB evolutionary models of Miller Bertolami (2016) for solar-like metallicities ($Z = 0.01, 0.02$) yields an initial mass of the star of around $2 M_\odot$ or slightly higher. This corresponds to a luminosity of around $8000 L_\odot$. The modeling of the dust shell and SED of HD 161796 by Gledhill & Yates (2003) and Min et al. (2013) result in the star having a temperature consistent with our results and a luminosity of around $3000–3400 L_\odot$. However, they adopted a 1.2 kpc distance to the star, which was derived by Skinner et al. (1994). This value, as its authors state, is extremely sensitive to the choice of surface temperature, for which they adopted $6300$ K (Fernie 1983), which was in turn derived by not taking into account circumstellar absorption. The latest release of the Gaia data has resulted in a distance of $1.9$ kpc to HD 161796 (Bailer-Jones et al. 2021). If such a distance had been used in the SED modeling, the luminosity would rise to around $7500–8500 L_\odot$.

We find a good agreement between our results and the model predictions (Miller Bertolami 2016) for surface abundances of CNO elements. Our surface abundances corrected for non-LTE

**Figure 5.** Photospheric abundances as a function of chemical element dust condensation temperature. The values for $T_{\text{cond}}$ are taken from Lodders (2003). The abundances for C, N, O, S, and Zn are corrected for non-LTE effects.

5.14 and 4.14 eV. It seems that the inclusion of non-LTE effects would not lower the Na abundance ($[\text{Na/H}] = 0.28$) enough, since for one of the three weak lines we measure ($5682.63 \AA$) extrapolation of the Lind et al. (2011) results suggests a correction of only around $-0.2$ dex. For K, it is hard to more or less reliably extrapolate to the temperature and surface gravity of HD 161796 from the grid of the Reggiani et al. (2019) non-LTE corrections. Even if we were to use the largest value of $-0.9$ dex that they find for giants of 6000 K surface temperature, the potassium abundance would still be somewhat too high with respect to some of the elements with FIPs of around 6 eV. We point out that the observed depletion, although not very pronounced, makes HD 161796, with its shell-type SED (Hrivnak et al. 1989), an interesting case among the depleted post-AGB objects, since Gezer et al. (2015) found all of them to have a disk-type SED, with a few exceptions of objects with no IR excess.

4.3. Pulsational Properties

Pulsation is the main reason for atmospheric parameter variation in HD 161796. We find a 420 K peak-to-peak amplitude for the effective temperature from the analysis of our spectra. Based on color variation, Hrivnak et al. (2015) estimated that the effective temperature of HD 161796 due to pulsation may change by 700 K. We observe two significant pulsation-related correlations for atmospheric parameters (Figure 6). First, the increase in effective temperature is accompanied by an increase in surface gravity. This agrees well with the conclusion of Hrivnak et al. (2018) that HD 161796 is in the hottest and brightest phase of pulsation when it is smallest in size, which is based on $\sim 0.25$ period phasing between the color and radial velocity curves. The light and color curves are observed to be approximately in phase. Second, the higher radial velocity corresponds to a lower surface temperature. In this case, our result suggests that the temperature and radial velocity variations might actually be in phase; however, bearing in mind the complex pulsation nature of HD 161796, our limited number of spectra that are associated with different pulsation cycles, and the fact that Hrivnak et al. (2018) observed the star in more pulsation phases than we do (with $V_r$ in the range from $-60.7$ to $-46.2$ km s$^{-1}$ compared to our $-55.6$ to $-49.6$ km s$^{-1}$), the phasing of $\sim 0.25$ periods cannot be excluded. The luminosity of a star can be calculated using the following equation:

$$ L = 4\pi G\sigma MT_{\text{eff}}^4/g, $$

where $G$ is the gravitational constant, $\sigma$ is the Stefan–Boltzmann constant, and $M$ is the current mass of the star.
effects and expressed in mass ratios are $X_0/X_C = 3.9$ and $X_C/X_N = 2$. For a $1M_\odot$ initial mass with $Z = 0.02$, the model predicts $X_0/X_C = 3.3$ and $X_C/X_N = 1.6$. For $1M_\odot$, $Z = 0.01$ and $1.25M_\odot$, $Z = 0.02$, these values are $X_0/X_C = 3.6$ and $X_C/X_N = 1.3$. For all higher-mass models, $X_C/X_N > X_0/X_C$, with the exception of the $4M_\odot$, $Z = 0.02$, model where the calculations result in $X_0/X_C = 1.6$ and $X_C/X_N = 0.4$.

Although the photospheric parameters alone correspond to an initial mass of the star of $\sim 2M_\odot$, the surface abundances and low evolutionary rate suggest the possibility of lower mass. Therefore, we conclude that the initial mass of HD 161796 is $\lesssim 2M_\odot$ (a current mass of approximately 0.58 $M_\odot$ or slightly lower).

Arellano Ferro et al. (2003) estimated the luminosity of HD 161796 and a few other post-AGB stars based on absolute magnitude−777 nm oxygen triplet EW calibration. They measured the EW of the whole triplet to be 2.01 Å and arrived at a significantly more luminous $(\log(L/L_\odot) = 4.9)$ and, consequently, more massive star than our results suggest. By directly integrating the profiles, we find different EWs for the triplet in different spectra, ranging from 1.55 Å for the 2021 May spectrum to 2.18 Å for the 2005 spectrum. These values do not seem to be correlated with any of the derived photospheric parameters, radial velocity, or luminosity estimated from Equation (2). It has been noted by Takeda et al. (2018) and Kovtyukh et al. (2012) that the use of the 777 nm O I triplet calibration for low-mass and low-gravity post-AGB stars could give faulty results, since the calibration has been derived for normal, massive supergiants. HD 161796 serves as evidence that the calibration is not applicable to post-AGB stars, at least not to all of them.

5. Summary

Multiple high-resolution optical spectra of the post-AGB star HD 161796 acquired during the last 18 yr are analyzed with the main goal of determining the evolutionary increase in temperature and comparing it with the latest models of post-AGB star evolution. Photospheric parameters of the star are derived by homogeneous analysis of absorption-line EWs from spectra of different epochs. This results in different values for $T_{\text{eff}}$, ranging from 7080 to 7500 K, and for log $g$, from 0.5 to 1.0 dex, with the average values being 7275 K and 0.7 dex. The use of a quasi-static approach to model the pulsating atmosphere of the star is the likely reason for the different iron abundances for different spectra: the log $\varepsilon$(Fe) values range from 7.3 to 7.5 dex, with the average being 7.44 dex—higher than in previous studies. We find correlations for effective temperature with the surface gravity and radial velocity of the star. It is confirmed that for HD 161796, during pulsation, the stellar surface is hotter when the star is smaller in size. The relatively large pulsation-related variation in $T_{\text{eff}}$ does not allow us to derive a precise evolutionary rate; nevertheless, we are able to conclude that it is slow. Abundance analysis is done, and it suggests that the star has suffered from dust−gas separation. Photospheric parameters, the low evolutionary rate, and the surface abundances suggest that HD 161796 has evolved from a star with an initial mass of $\lesssim 2M_\odot$. It is confirmed that the use of the 777 nm O I triplet calibration to derive the luminosity of stars can provide faulty results for post-AGB objects. Signatures of shock-wave presence in the atmosphere are observed as splitting and significant temporal variation in strong spectral lines. Variable incipient mass loss is suggested by Hα profiles and their variations. HD 161796 experiences warm variable outflow from its surface, which explains the fact that most medium-strength lines have variable blue wings and central parts, while the red wings remain stationary. Further studies of high-resolution spectra of HD 161796 could prove useful in understanding the stellar wind in the post-AGB phase.

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Software: DECH (http://www.gazinur.com/Spectra-Processing.html), SPECTRUM (Gray & Corbally 1994), iSpec (Blanco-Cuaresma et al. 2014).

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