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Monitoring of dynamical processes in outer atmospheres of cool protoplanetary nebulae

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Abstract. Dynamics in the atmospheres of central stars of cool protoplanetary nebulae can contribute to shaping of the subsequent planetary nebulae by giving rise to stellar wind. We have investigated variation in high-resolution spectra of three relatively cool post-asymptotic giant branch stars that are surrounded by non-spherical nebulae. Spectra of HD 161796 show variability in blue wings of weak and medium strength absorption lines while red wings remain unchanged. This could be caused by warm variable outflow. An episode of infall of matter is revealed in spectra of IRAS 22272+5435. Also, episodes of molecular lines in emission are detected for this star. The emissions appear to be related to the star's brightness changes. Qualitatively the same molecular line variability is observed in the spectrum of IRAS Z02229+6208. Possibly, the observed spectral variations are a consequence of similar dynamics as in the atmospheres of asymptotic giant branch stars.

Keywords. stars: AGB and post-AGB, stars: atmospheres, stars: winds, outflows, stars: individual (HD 161796, IRAS 22272+5435, IRAS Z02229+6208)

1. Introduction

Outflows that originate in the atmospheres of post-asymptotic giant branch (post-AGB) stars, including central stars of protoplanetary nebulae (PPNe), are poorly understood, especially in the case of the coolest objects. While the progenitors – AGB stars – have dust-driven winds (Höfner & Olofsson 2018), and hot post-AGB stars develop line-driven winds (Krtička et al. 2020), the nature of the outflow immediately after the termination of AGB is unclear. As the star reaches post-AGB phase the mass-loss rate decreases by orders of magnitude, but in early stage of this phase it could still be significant (Schönberner & Steffen 2007). Additionally, mass loss exactly on this early stage has a considerable impact on evolution of the star (Miller Bertolami 2016). Although binary interactions are generally thought to be responsible for shaping the nebula surrounding the star, also the wind from the central star itself can have an impact.

We present results of investigation of spectral variability of three relatively cool central stars of PPNe: HD 161796 (Puķītis et al. 2022), IRAS 22272+5435 (Začs & Puķītis 2021; Puķītis et al. 2023), and IRAS Z02229+6208 (Začs & Puķītis 2023). All of the stars have shell type spectral energy distribution (Gezer et al. 2015) and for none of the stars there is conclusive evidence for binarity (Hrivnak et al. 2017; Parthasarathy 2022; Hrivnak et al. 2022). All three PPNe are of non-spherical form (Ueta et al. 2000).

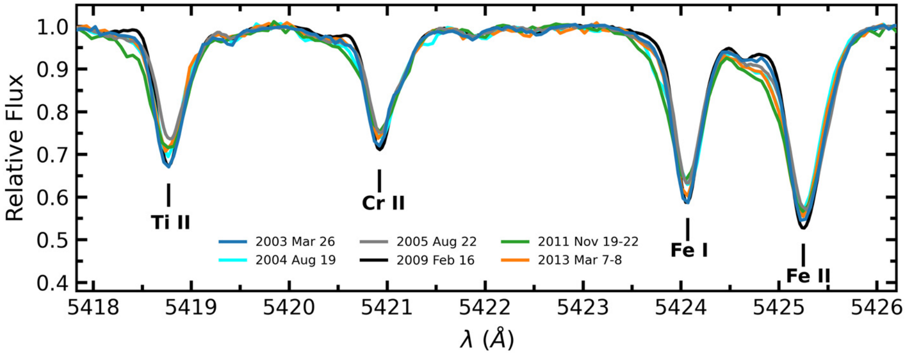

Figure 1. Typical variation of medium-strength absorption lines in spectrum of HD 161796.

2. HD 161796

HD 161796 is an oxygen-rich post-AGB star with surface temperature of around 7200 K (Takeda et al. 2007). This PPNe object pulsates with a primary period of around 45 days (Hrivnak et al. 2015). We compared multiple spectra of the star, that have been acquired during the time span from 2003 to 2021, and detected variability in red wings as well as in central parts of weak and medium strength absorption lines while blue wings remain unchanged (Figure 1). Such behaviour is seen for virtually every line irrespective of the chemical element, ionization stage, and excitation potential. We interpret this variability to be caused by warm variable outflow from the stellar surface. This idea is corroborated by variations in the strong lines. The shape of Hα line in HD 161796, as interpreted by Sánchez Contreras et al. (2008), is a combination of atmospheric absorption and emission that forms in close stellar surroundings and is caused by shocks. Spectra of the star show the central emission-related part of the Hα profile to be highly variable. Profiles of some other strong absorptions also indicate presence of shocks, for example, Fe II 5169.03 Å line clearly shows splitting in some epochs (Figure 2).

3. IRAS 22272+5435

The carbon-rich post-AGB star IRAS 22272+5435 has a surface temperature of around 5500 K (Začs et al. 2016), and it pulsates with a primary period of approximately 132 days (Hrivnak et al. 2022). Two sets of spectra were investigated to search for interday variability. No short-term variability was seen in six spectra acquired within 7 days in 2011 November, when the star was at pulsation phase light minimum. On the other hand, seven spectra observed within 11 days during light maximum phase in 2010 September show significant variability in CN Red (1,0) absorption lines as they increase in radial velocity and decrease in intensity (Figure 3). For example, CN 9203 Å line changes velocity with respect to the photosphere from approximately +16 to +23 km s^{-1} while its equivalent width decreases from 80 to about 20 mÅ. The variation suggests an infall of matter from a height of no less than 25 $R_{\odot}$ above the photosphere. The decrease in intensity is probably related to increase in temperature due to inward motion. Also strong metal absorption lines bear evidence of infall. These lines have photopsheric and additional redshifted absorption component. This excess absorption increases its radial velocity; however, the radial velocity range is different than for CN Red (1,0) lines, presumably due to formation in different heights.

By comparing 2015-2017 spectra of IRAS 22272+5435, we notice numerous emission lines at some epochs and identify them with the CN Red and C_2 Swan system transitions (Figure 4), that belong to multiple vibrational bands. For example, 2015 September 22 spectrum is one of the spectra with the most intense observed emissions reaching up to

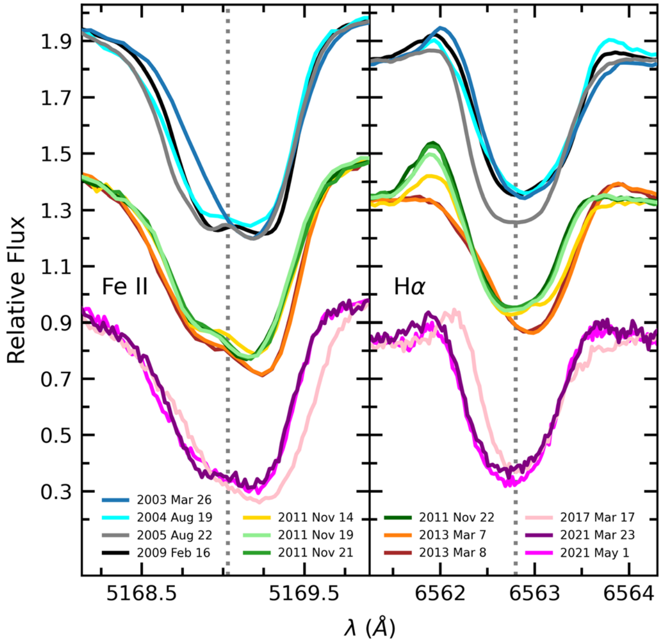

Figure 2. Variability of Fe II 5169.03 Å line and the central part of the Hα profile in the spectrum of HD 161796.

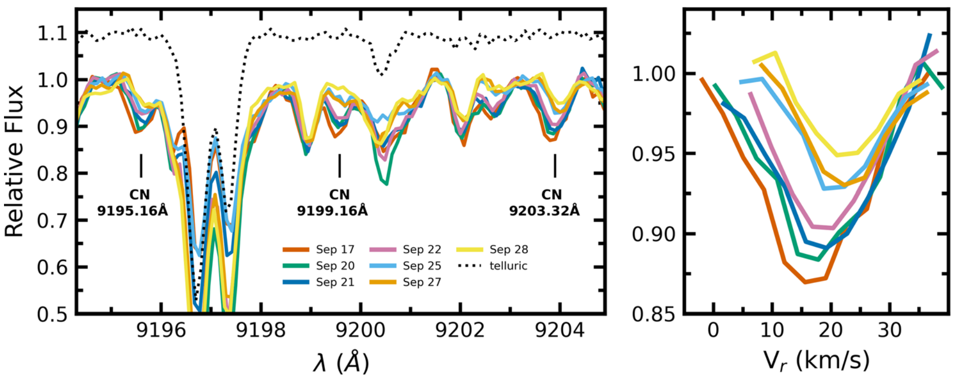

Figure 3. Left: some CN Red system (1,0) lines in 2010 September spectra of IRAS 22272+5435. Right: variability of CN 9203.32 Å line in radial velocity scale with respect to the photosphere.

10 % and even more above the continuum level. Emissions from high rotational quantum number (J) transitions are detected. For example, in the case of CN Red (1,0) and (2,1) bands the emissions are seen in lines arising from transitions with J up to around 70. The spectra suggest that it takes around 2-3 weeks for emissions to reach maximum observed intensity or to decrease to absorption. It appears that molecular emissions are related to pulsation of the star as they are seen only in those phases that are closer to light maximum than minimum. Also Začs et al. (2016) suspected weak CN Red (5,1) emission lines in spectra that were observed during light maxima. However, for example, in 2017 October 31, that corresponds to pulsation phase light maximum, molecular spectrum is described by absorptions. The emissions have radial velocities that are shifted by up to few km s^{-1} with respect to the centre of mass velocity of the star and do not

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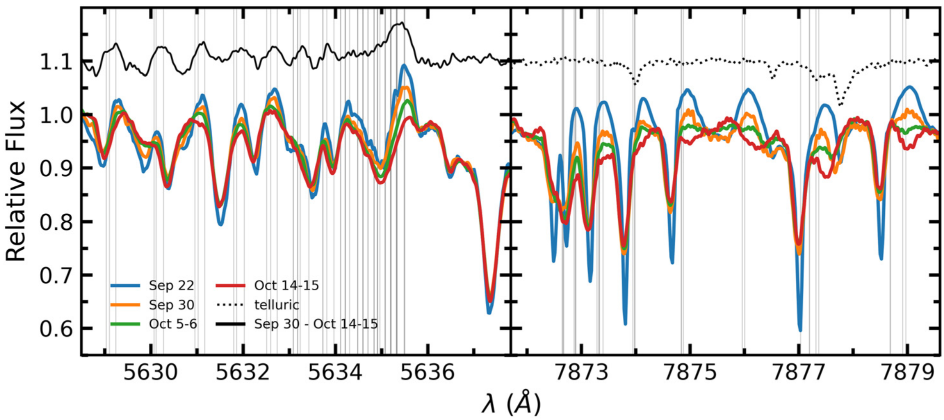

Figure 4. Molecular emissions in the 2015 September-October spectra of IRAS 22272+5435. Left: changes in the C_2 Swan system (0,1) bandhead. Positions of the strongest (highest oscillator strength) molecular lines are marked by vertical gray lines. Subtraction of October 14-15 from September 30 spectrum illustrates the variability that is partially masked by absorptions. Right: variation in the CN Red system (2,0) lines. Along with the slightly redshifted variable emissions also narrow blueshifted CSE absorptions are visible.

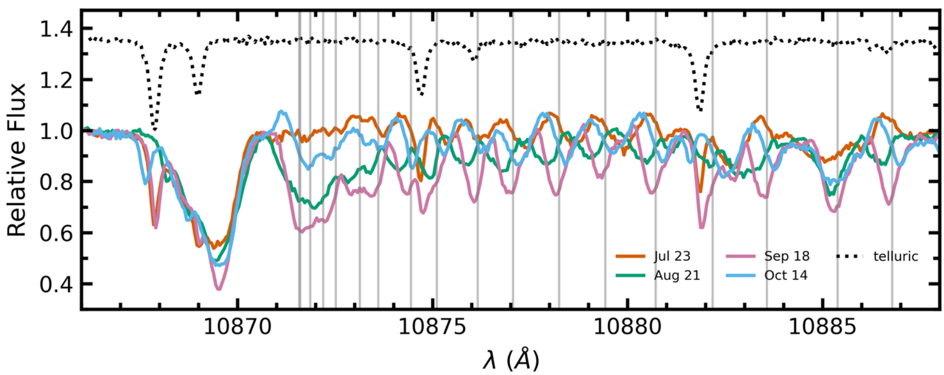

Figure 5. CN Red system (0,0) lines in the 2022 spectra of IRAS Z02229+6208. Vertical gray lines mark the wavelengths of the strongest CN Red system (0,0) lines.

appear to follow pulsation of the star. Some weaker components can have larger shifts, for example, in the September 22 spectrum the emissions are accompanied by weak absorption located at around -12 km s^{-1}. On this epoch the emission lines have a full width at half maximum that corresponds to 13 km s^{-1}. The absorptions, that emissions appear to precede or succeed, are broader than the absorption lines that are formed in the circumstellar envelope (CSE). The relatively fast changes and the widths of the molecular lines suggest that the emissions are formed close to the star. The observed velocities of the molecular features are similar to typical velocities found in modelling of AGB star atmosphere dynamics. Perhaps, similar processes, such as shocks and large scale convection, are responsible for the molecular line behaviour in IRAS 22272+5435.

4. IRAS Z02229+6208

The carbon-rich post-AGB star IRAS Z02229+6208 has a 5500 K surface temperature (Reddy et al. 1999) and primary pulsation period of around 155 days (Hrivnak et al. 2022). We observed it four times in 2022 over a single pulsation cycle. Most notability, we detect variability in CN Red lines (Figure 5) belonging to multiple vibrational bands.

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Overall, the molecular lines behave in a qualitatively similar fashion as in the case of IRAS 22272+5435 – shapes, intensities and radial velocities are alike. Also the apparent correlation of emissions with the pulsation of the star is present. The observed molecular line behaviour could be common for the coolest carbon rich post-AGB stars.

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