Following V509 Cas into the void with FIES

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Abstract

V509 Cas is one of the rare evolved massive stars known as yellow hypergiants. These stars are in an unstable phase of evolution, during which their atmospheres undergo recurring outbursts. Over the 20th century, V509 Cas went through multiple eruptive mass-loss episodes, during which its temperature, luminosity and other physical parameters changed rapidly. At the beginning of the 21st century, the behaviour of V509 Cas suddenly changed and the star started to show signs of reaching a more stable phase of evolution. Using the FIbre-fed Echelle Spectrograph (FIES) at the Nordic Optical Telescope, we have explored the surface movements of the star to get a glimpse of its circumstellar environment and we have found confirmation to the hypothesis of a disc surrounding the star.

Keywords: stars: massive, evolution; techniques: spectroscopic

1 Introduction

Yellow hypergiants (YHGs) are massive stars ($m > 8$ M$_\odot$) that belong to the Ia$^+$ luminosity class. They have extended photospheres and a relatively large rate of mass loss. On the Hertzsprung-Russell (HR) diagram they are located near the upper luminosity limit, among the brightest stars (de Jager, 1998). The effective temperatures of YHGs are in the range of 4000–8000 K and they have zero-age main sequence (ZAMS) masses of 20–40 M$_\odot$ (Nieuwenhuijzen et al., 2012). Over the course of evolution they have lost at least half of their initial mass (de Jager and Nieuwenhuijzen, 1997). It has been proposed that YHGs are evolving on the HR diagram blueward, towards the higher temperatures, having previously completed the red supergiant (RSG) stage (de Jager, 1998).

The region of the HR diagram where yellow hypergiants can be found, has been named by de Jager (1998) 'the yellow evolutionary void' due to the scarcity of blueward-evolving stars. When approaching the border of the void, stars exhibit extreme instability, as the effective gravity $g_{\rm eff}$ in the atmosphere approaches very small or near-zero values. Small perturbations - such as pulsations - can spark a mass loss episode from the star (de Jager, 1998). In an event of eruptive mass loss the star develops an envelope of cooler ejected matter, leading to a sudden decrease in the star's effective temperature. It is not known, how frequently and how many times these enhanced mass loss events can happen and if the star can pass through the void (Israelian et al., 1999). However, YHGs are eruptive on a timescale of decades or even less (van Genderen et al., 2019).

1.1. History of V509 Cas

V509 Cas is a hot yellow hypergiant star with a spectral type A outside the outburst phase (Aret et al., 2017). Over the course of the 20th century, V509 Cas has suffered two episodes of enhanced mass-loss: first in 1970 and second in 1979–1982. During both of these episodes the temperature of the star dropped suddenly by an order of several hundred degrees, after which it increased again slowly. The star seemed to 'bounce' twice against the low-temperature border of the yellow void. Along with the periods of enhanced mass-loss, the effective gravity g_{eff} became negative, i.e. the outer layers of the star became gravitationally detached. After the latest mass-loss episode, the temperature started to increase rapidly, reaching around 7500 K by the mid-1990s (de Jager and Nieuwenhuijzen, 1997). These large variations of effective temperature ($\Delta T \sim 3000 - 4000$ K) in V509 Cas are not caused by pulsations, but rather could be caused by evolutionary changes inside the stellar interior (Israelian et al., 1999). Schuster et al. (2006) found no indication of distant nebulosity around the star. Although the star is losing mass at a rapid rate ($\sim 10^{-5} M_{\odot}\mathrm{yr}^{-1}$ (Israelian et al., 1999)), substantial mass-loss like this cannot have lasted more than 10^3 years.

In the mid-1990s, a new mass-loss episode in V509 Cas was expected to be imminent (de Jager and Nieuwenhuijzen, 1997), however it didn't happen. Instead, the temperature of the star stabilised near 8000 K (Nieuwenhuijzen et al., 2012). Along with the stabilising temperature of the star, based on AAVSO V-filter observations, the brightness of V509 Cas has remained almost constant from the early 1990s onwards (van Genderen et al., 2019).

1.2. The circumstellar environment around V509 Cas

The environment of V509 Cas, where spectral lines are formed, can be divided into three parts (Lambert et al., 1981): (i) the H II region is furthest from the star and there form a portion of Hα emission and the [N II] lines, which are very rare in the spectra of such cool stars; (ii) the circumstellar shell, which includes the outermost layers of the extended atmosphere: from there could originate the emission lines from neutral (Lambert et al., 1981) and low-excitation ionised atoms (Klochkova, 2019); (iii) the photosphere of the star, where the spectral lines (e.g. Si II and N I) show large variations in line profile shapes and radial velocity. The behaviour of photospheric metallic lines in the spectrum of V509 Cas is linked to its pulsations.

V509 Cas is a quasi-periodic variable. Its pulsations are expected to be non-radial (Arellano Ferro, 1985), but their behaviour is cyclic without any gaps, indicating an instability pattern that consists of numerous such pulsations that cover the entire stellar surface. Quasi-periods and their amplitudes in the light curve depend on the star's effective temperature. If the star is hotter, periods are shorter and amplitudes are smaller and if the star is cooler, periods are longer and amplitudes are larger (van Genderen et al., 2019). Percy and Zsoldos (1992) found that in the 1980s periods ranged between 200 and 400 days, based on light curves. Van Genderen et al. (2019) showed that the quasi-periods of V509 Cas have decreased linearly between 1976 and 1993 to 100–150 days, which coincides with the gradual heating of the star. The pulsational behaviour of YHGs is intertwined with their effective temperatures.

V509 Cas has a distant and hot B1 spectral class companion (Stickland and Harmer, 1978). However, the role of the companion appears to be limited to ionising the most distant envelope around V509 Cas, causing the appearance of the [N II] lines in the spectrum (Lambert et al., 1981).

[Ca II] $\lambda\lambda$7291,7324 lines and [O I] $\lambda\lambda$6300,6364 lines have been detected in spectra of V509 Cas (Aret et al., 2017; Klochkova, 2019). Similarly to V509 Cas, the spectrum of the YHG ρ Cas has [Ca II] emission lines of circumstellar origin (Kraus et al., 2019). The presence of both sets of forbidden lines also in B[e] supergiants (B[e]SGs) indicates that the circumstellar environments of these stars could be similar (Aret et al., 2017).

[Ca II] lines have been found to be reliable tracers for disc-like structures around B[e]SGs. There, the [Ca II] lines are formed in a rotating Keplerian disc, quite close to the star in higher density regions of the disc. [O I] lines are formed further away. The forbidden lines for the observed B[e]SG stars were double-peaked, indicating rotational broadening (Aret et al., 2012).

The evolutionary phase of B[e]SG stars has been suggested to be post-RSG or post-YHG (Davies et al., 2007). As YHGs continue their journey into the void, they could continually lose mass that accumulates onto the equatorial plane, so that if the star eventually reaches the blue high-temperature edge of the void, it would appear as a B[e]SG (Aret et al., 2017). For one YHG (IRC+10420) Davies et al. (2007) found evidence that the star is moving towards the B[e] supergiant phase.

2 Observations

Long-term monitoring observations of V509 Cas (years 2015–2022) have been done in Tartu Observatory (TO) with the 1.5 m telescope AZT-12 using a long-slit spectrograph in the Cassegrain focus. We used 1800 lines mm^{-1} grating with resolution R=10 000 and the CCD Andor Newton DU970 1600x200 pixels. The spectra were taken in the wavelength region 6300–6600 Å with signal-to-noise ratios between 200-300. For wavelength calibration, we used comparison spectra from a ThAr lamp, taken before and after the target exposure(s). The data were reduced and heliocentrically corrected with standard IRAF[1] procedures. To increase the precision of the radial velocities, we improved the wavelength scale using telluric lines and FIES spectra of V509 Cas. Thanks to FIES, we determined the wavelength of a DIB line at $\lambda 6379.00 \pm 0.01$ Å, which is in wavelength scale close to the Si II lines that we used to determine the radial velocity of the stellar surface. The correction of the wavelength scale provides a precision of radial velocities found from TO spectra 0.54 km s^{-1}.

In 2021–2022 we obtained high-resolution spectra of V509 Cas at the Nordic Optical telescope (NOT) at the Roque de los Muchachos Observatory with FIES[2] in med-res (R=45 000) mode. The spectral range for FIES spectra is 3630–8980 Å without gaps. Observations have signal-to-noise ratios between 130 and 250. The data were reduced with the FIEStool[3] software. The resulting spectra were normalised to continuum around the spectral regions of interest. Additionally, the removal of telluric lines was performed using a hot fast-rotating star 68 Cyg as a telluric standard.

3 Results and Discussion

We have over 7 years of data collected at TO and almost one year of data collected with FIES at the NOT, with a cadence of about 1 month. During this time, we have observed variability in the radial velocity, temperature and shape of many spectral lines (e.g. Hα, Sc II, Fe II, [Ca II], Si II). In this paper, we concentrate on [Ca II], Fe II and Si II lines and their implications for the circumstellar environment.

The quasi-periodic oscillations of luminosity and radial velocity in YHGs are caused by dynamics in the star's atmosphere. This manifests in the variability of photospheric absorption lines that are formed at different depths. The average radial velocity over the last 7 years based on Si II lines in TO and FIES spectra is -60.9 km s^{-1}. For Si II Klochkova et al. (2019) found velocities of -59 km s^{-1}, which is consistent with our results. The standard deviation of radial velocities over our observed period is 3.8 km s^{-1} with a maximum difference 21.9 km s^{-1}

Pulsations cause variability in both the radial velocity and shape of spectral line profiles. In Figure 1 we have plotted FIES observations of Fe II, [Ca II] and Si II lines in velocity scale. Si II is a strong absorption line, [Ca II] line is double-peaked similarly to B[e]SG stars and Fe II has both absorption and emission components. It is shown in the figure, how the intensity of the absorption and emission

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[1] IRAF: `https://iraf.net/`

[2] FIES: `http://www.not.iac.es/instruments/fies/`

[3] FIEStool: `http://www.not.iac.es/instruments/fies/fiestool/FIEStool.html`

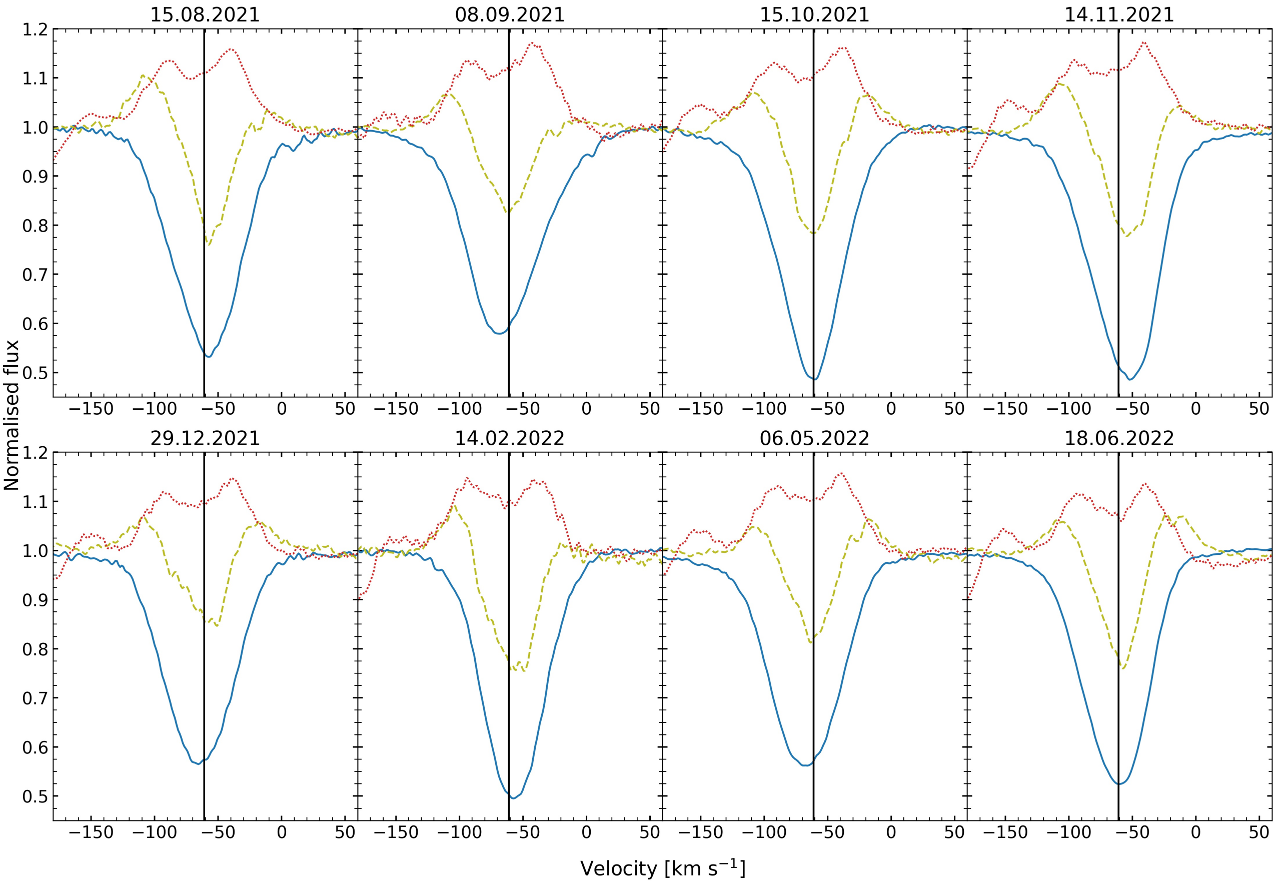

Figure 1: Snapshots of Fe II λ7712 (green dashed line) and [Ca II] λ7324 (red dotted line) spectral lines throughout one year show variability of both the absorption and emission components. The [Ca II] lines are clearly double-peaked, while the Fe II lines show both emission and absorption components of varying intensities. The Si II λ6347 (blue solid line) absorption line varies both in wavelength and relative intensity synchronously with the Fe II absorption component. The average radial velocity based on the TO and FIES spectra is indicated by a black vertical line. Displayed spectra are from FIES in medium resolution mode.

components of the Fe II line change significantly while the [Ca II] line remains much more stable. Variations in the Si II line are a good indication of the mean movement of the stellar surface due to pulsations (Lambert et al., 1981). The absorption component of the Fe II line varies synchronously with Si II absorption, indicating that they originate from the same layer of the stellar atmosphere. Meanwhile, the double-peaked [Ca II] line barely shows any change: this line's formation has been linked to a disc structure surrounding the star and therefore it is not affected by underlying pulsations. The emission components of the Fe II line are formed at similar velocities to the two peaks of the [Ca II] line. The relative intensities of these emission components seem to be linked to the star's pulsational cycle. When the absorption component is more redshifted, the higher-velocity emission wing is relatively weaker. The opposite is also true - when the absorption is more blueshifted, the lower-velocity wing is weaker. In such a way, the resulting line profile of Fe II is formed at two different layers of the environment of V509 Cas: the absorption component in the star's photosphere, behaving in accordance with the pulsational cycle and the emission components far away from the surface, their intensity is only determined by the current position of the absorption component. As the velocities of [Ca II] peaks and Fe II emission components are similar, so could the region of their formation -

similarly to [Ca II], the emission components could originate from a disc around V509 Cas.

4 Conclusions

We present a brief overview of a few interesting spectral features of V509 Cas (Si II, [Ca II] and Fe II spectral lines) that have been observed with FIES at the NOT in 2021–2022. These lines originate from different layers of the environment of V509 Cas, giving us valuable insight into the current circumstellar structure and hints to what the future could hold. Both Si II and Fe II absorptions show photospheric pulsational variability, while the emission components in the wings of Fe II lines could originate from a different region of the circumstellar environment. Their velocity profile is similar to the stable [Ca II] line, which is a known tracer for disc structures in B[e]SGs. The variability of the emission components of Fe II can be explained by the sum of a relatively stable emission component originating from the disc and a pulsationally variable (in both radial velocity and depth) absorption component. This strengthens the hypothesis of a disc around V509 Cas and provides another connection between the evolutionary states of B[e]SGs and YHGs.

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