Received 14 May 2025; | Revised 20 May 2025; | Accepted 25 May 2025

DOI: xxx/xxxx

ORIGINAL ARTICLE

Spectroscopic observations of CI Camelopardalis: Evidence for stratified circumstellar environment and variable radial velocities

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Present Address

Abstract

We present high-resolution spectroscopic observations of CI Camelopardalis, a remarkable binary system consisting of a B[e] star and a compact object, obtained with the Ondřejov Echelle Spectrograph. Our analysis reveals distinctive emission profiles that indicate a stratified circumstellar environment with evidence of temperature and density gradients. The complex profiles of Hα and other emission lines show characteristic two-peak structures with asymmetrical intensity ratios (V/R), suggesting the presence of spiral density waves in the circumstellar disk. Comparison with archival data shows significant variability in radial velocities, with our measurements displaying the most redshifted values among available observations. Of particular interest is the detection of a strong O I 8446Å emission line alongside the absence of the O I 7771-7775Å triplet, indicating Lyman-β fluorescence as the dominant excitation mechanism. The forbidden [N II] lines provide an estimate of the systemic velocity of approximately -25 km/s, which differs from previously published values. We interpret our findings in the context of a model with a stratified circumstellar disk around the primary B-type star, periodically perturbed by a compact companion on an eccentric orbit.

KEYWORDS:
stars: emission-line, Be, stars: individual: CI Cam, binaries: close, circumstellar matter, techniques: spectroscopic

1 | INTRODUCTION

CI Camelopardalis (CI Cam) is a remarkable stellar system that gained significant attention following its intense outburst in 1998, which was detected across the electromagnetic spectrum. The system represents a unique combination of astrophysical phenomena, providing a rare opportunity to study the interaction between a massive star and a compact object. This interaction creates a rich emission spectrum with complex profiles reflecting the diverse physical processes occurring within the system.

CI Cam is classified as a B[e] binary system (1), with a primary B-type star surrounded by an extensive circumstellar disk. The secondary component is a compact object, likely a white dwarf or neutron star (2). The system has been the subject of numerous studies aiming to understand its nature and the physical processes driving its unusual behavior.

Interferometric observations in the infrared (3) have revealed that the dust disk around the B star has an outer radius of approximately 38 AU (assuming a distance of 5 kpc) and is inclined at an angle of 67° relative to the observer's line of sight. Barsukova et al. (4) identified the He II 4686Å emission line in the spectrum of CI Cam, with radial velocity variations ranging from approximately -250 to +120 km/s. They associated this line with the compact component of the system and derived that it follows a highly eccentric orbit (e = 0.44-0.49) with a period of 19.407 days. The semi-major axis of this orbit

[0]**Abbreviations:** OES, Ondřejov Echelle Spectrograph

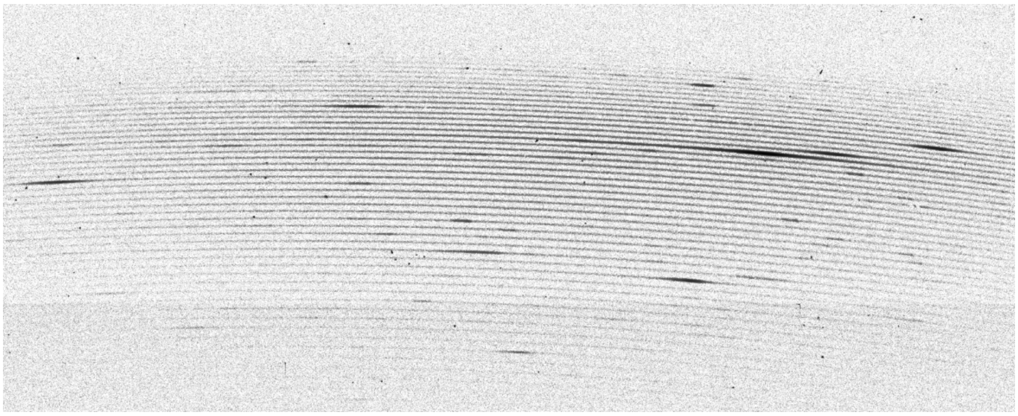

FIGURE 1 Echellogram of CI Cam from the Ondřejov Echelle Spectrograph (OES). Bright emission lines are clearly visible against the relatively weak continuum. The brightest line in the upper right is the Balmer hydrogen line Hα.

is approximately 0.35 AU, bringing the compact component to within 38-42 $R_\odot$ of the primary star at periastron, while it recedes to 108-112 $R_\odot$ at apastron.

The motions of the He II emission line are in anti-phase with the motions of lines originating in the disk of the B star, confirming their origin in the vicinity of the compact component. This complex orbital configuration leads to periodic perturbations of the circumstellar disk, which manifests in the spectral characteristics of the system.

In this paper, we present new high-resolution spectroscopic observations of CI Cam obtained with the Ondřejov Echelle Spectrograph (OES). We analyze the profiles of various emission lines, focusing on their shapes, widths, and radial velocities. We compare our findings with archival data and interpret the results in the context of a model involving a stratified circumstellar disk periodically disturbed by the compact companion.

2 | OBSERVATIONS AND DATA REDUCTION

Spectroscopic observations of CI Cam were conducted using the Ondřejov Echelle Spectrograph (OES) at the Astronomical Institute of the Czech Academy of Sciences in Ondřejov. The OES is mounted on the 2-meter Perek telescope, the largest telescope in the Czech Republic, and provides high-resolution spectra (R = 32,000) across multiple orders.

The observations were carried out in February 2025. The high resolution of the spectrograph enables the detection of radial velocities with an accuracy of approximately 10 km/s, which is sufficient for monitoring the dynamic processes in the system, including orbital motion and the movement of matter in the circumstellar environment.

The raw echelle spectra were processed using standard procedures in the IRAF software package, specifically with routines in the `noao.imred.echelle` module (5). This processing included bias subtraction, flat-field correction, wavelength calibration using ThAr comparison lamp spectra, and extraction of individual orders. The extracted spectra were then normalized to the continuum level for further analysis.

The OES spectrograph has 54 usable orders, covering a wide wavelength range that includes numerous spectral lines of interest for studying the CI Cam system. For our analysis, we focused particularly on the emission lines of hydrogen (Hα, Hβ), helium (He I), iron (Fe II), oxygen (O I), and nitrogen ([N II]), as these are the most prominent features in the spectrum and provide valuable information about the physical conditions and kinematics of the various components of the system.

Figure 1 shows the echellogram of CI Cam obtained with the OES. The prominent emission lines are clearly visible against the relatively weak continuum, with the Hα line being particularly intense.

3 | RESULTS

3.1 | Emission Line Profiles and Their Variability

Detailed analysis of the obtained spectrum revealed several key characteristics of the emission lines in CI Cam. The Fe II lines exhibit typical "rectangular" profiles with steep edges and concave tops. In our observations, these lines have two characteristic peaks at radial velocities of approximately -55 km/s and +15 km/s, with their intensity ratio (V/R) significantly greater than 1 (approximately 1.8 for Fe II 6456.383Å). This indicates that the part of the disk moving toward the observer is systematically brighter than the part moving away from the observer.

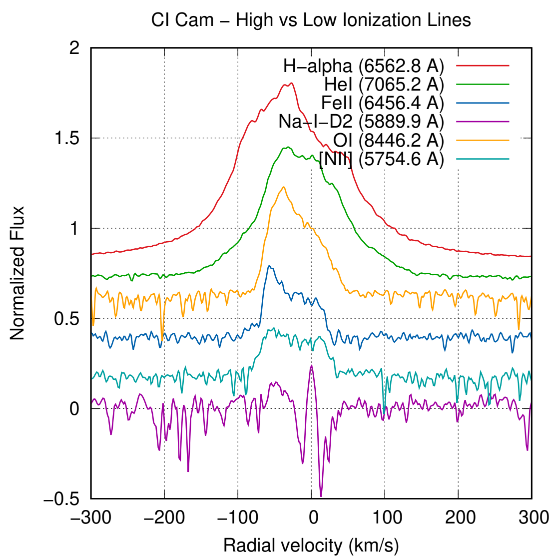

FIGURE 2 Profiles of lines of different atoms in the spectrum of CI Cam showing progressively widening emission profiles from Fe II through He I to hydrogen lines.

Comparison with archival spectroscopic data shows that these profiles exhibit some variability depending on the orbital phase of the system, but the basic characteristics remain stable. This suggests a long-term stable geometry of the circumstellar environment, which is only periodically disturbed by the passage of the compact component.

An interesting aspect is the comparison of profiles of different elements (Figure 2). The He I lines also show a double profile, but with peaks at radial velocities of -30 km/s and +5 km/s and with an intensity ratio of approximately 1.1. The mean velocity between the peaks in He I lines is thus about 17.5 km/s, while in Fe II lines it is around 35 km/s, roughly twice the value. This significant difference provides direct evidence of the temperature profile of the circumstellar disk - while Fe II lines originate in cooler outer regions, He I lines with higher excitation potential form closer to the central star, where temperatures and rotational velocities are higher.

The Hα line exhibits an even more complex structure (Figure 4). Its profile includes broad wings reaching from -600 km/s to +400 km/s. The main maximum is located around -30 km/s, but the profile shows additional secondary peaks or breaks at -80 km/s and a prominent red-shifted component around +50 km/s, which creates a characteristic plateau. Remarkably, this structure around +50 km/s is present in all observed hydrogen lines but is absent in emission lines of other elements. It is also interesting that this structure is present only in our spectrum. In archival observations, this structure is missing, although otherwise the emission line profiles are very similar. The presence of the structure at +50 km/s only in our spectrum suggests that it is likely a transient phenomenon associated with a specific phase of interaction between the system components or with a random local density enhancement in the circumstellar environment.

3.2 | Significant Oxygen Lines

In our spectrum, we observed a very significant phenomenon - the presence of a strong O I 8446Å emission line with the simultaneous absence of the O I 7771-7775Å triplet. This pattern is a key indicator of the physical processes occurring in the system.

The O I 8446Å line is actually a triplet consisting of lines at wavelengths 8446.25Å, 8446.36Å, and 8446.76Å. These three lines are separated by only about 0.5Å and therefore usually appear as a single emission line except in spectra with the highest resolution. The triplet nature results from the fine splitting of atomic energy levels.

Strong emission of O I 8446Å with the absence or significant weakening of the O I 7771-7775Å triplet suggests that the 8446Å line is primarily excited by the Lyman-β fluorescence mechanism (also known as Bowen fluorescence) rather than collisional processes. In this mechanism, Lyman-β photons at a wavelength of 1025.7Å from hydrogen excite neutral oxygen atoms from their ground state (3P) to a specific excited state (3D), which subsequently transitions back by radiating an 8446Å photon. In contrast, the O I 7771-7775Å triplet is primarily excited by collisional processes and is not affected by Lyman-β fluorescence.

Another significant observation related to the O I 8446.25Å line is that its emission profile terminates at the same radial velocity around +50 km/s as the hydrogen lines. This match in kinematic properties suggests that oxygen and hydrogen emissions originate in the same region with a similar range of velocities. These matching kinematic properties, along with the Lyman-β fluorescence excitation mechanism, provide strong evidence for a close physical connection between hydrogen and oxygen emissions in CI Cam.

The presence of the Lyman-β fluorescence mechanism requires specific physical conditions, which typically include:

- A strong source of Lyman-β photons (hot gas or stellar photosphere)
- Regions with neutral oxygen atoms within reach of Ly-β photons
- Optical depth in the Lyman-β line that is not too high

This selective excitation is commonly observed in accretion systems, including some B[e] stars and young stellar objects with accretion disks. In the case of CI Cam, the presence of this mechanism further supports the interpretation of the system as an object with intensive accretion processes.

3.3 | Structure of the Sodium Doublet NaD

An interesting feature in our spectrum is also the sodium doublet NaD (5889.95Å and 5895.92Å), which has a complex structure combining both emission and absorption components (Figure 4). The profile of these lines contains several overlapping components with different origins.

We observe an absorption component of the NaD doublet, which extends in the range from approximately -20 km/s to +20 km/s. In the region with velocities lower than -20 km/s (greater blue shift), the profile transitions to an emission component, which has similar characteristics to Fe II emissions (approximately in the range -70 to -20 km/s). This emission component likely originates from the same region of the circumstellar disk as the Fe II emission, while the absorption component has an interstellar origin.

In the middle of the profile of both lines of the sodium doublet, there is a narrow emission line, which is not part of the CI Cam spectrum but comes from sodium lamps of our civilization. This so-called telluric (atmospheric) emission is part of the light pollution of the atmosphere and is common in astronomical spectra obtained by ground-based telescopes.

We observed the same structure in both lines of the sodium doublet NaD, which confirms the consistency of our observations. These lines thus provide a unique combination of information about both the CI Cam object itself, the interstellar environment, and even the Earth's atmosphere.

3.4 | Radial Velocities and Their Variability

A significant component of spectroscopic observations is the measurement of wavelength shifts and the determination of radial velocities according to the formula:

$$v_{\mathrm{rad}} = c\,\frac{\lambda_{\mathrm{obs}} - \lambda_{\mathrm{lab}}}{\lambda_{\mathrm{lab}}}$$

The centers of the vast majority of emission lines in our spectrum from OES are at a radial velocity of approximately -25 km/s. This value differs significantly from the published mean radial velocity of the system, which is approximately -35 km/s for regions associated with the B star (i.e., regions of Fe II, H, and He emission).

To verify this observation, we compared our data with archival spectra from the 2m telescope, taken with a single-order spectrograph with somewhat lower resolution, but still comparable to our data. This comparison confirms that the emission lines of CI Cam move as a whole and that our spectrum exhibits the "reddest" shift of all available observations (Figure 3). The bluest spectrum from 2018 is estimated to be about 25 km/s shifted compared to our spectrum, i.e., at approximately -50 km/s.

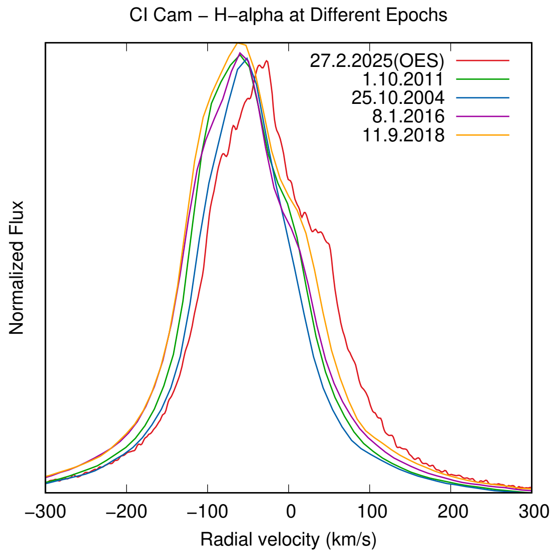

FIGURE 3 Comparison of the Hα profile from our observation and from archival data from 2004, 2011, 2016, and 2018. A systematic shift of radial velocities between individual observations is evident, with our spectrum showing the reddest shift.

The observed range of radial velocity variability (approximately 25 km/s) is comparable to the expected amplitude of orbital motion of the primary component in a system with a mass ratio corresponding to a B star (12-22 $M_\odot$) and a compact component (1-2 $M_\odot$).

3.5 | Forbidden Nitrogen Lines as Systemic Velocity Indicators

In our spectrum, we identified forbidden nitrogen lines [N II] 5754.59Å and, somewhat weaker, [N II] 6583.45Å with radial velocities of -25.9 km/s and -21.6 km/s, respectively. These nitrogen emission lines are often used to establish the systemic velocity of B[e] stars because they originate in low-density regions that are less affected by the kinematics of the rotating disk. Unlike Fe II lines, which exhibit characteristic "rectangular" profiles, [N II] typically has a simpler profile, and its radial velocity should better reflect the motion of the system as a whole. Klochkova et al. (6) determine based on this line the systemic velocity of CI Cam as -55.4 ± 0.6 km/s, while our measurement gives a significantly less negative value. This difference supports the idea that our measurement took place at a moment when the disk component is moving away from Earth on its orbit (and the compact component should conversely be approaching).

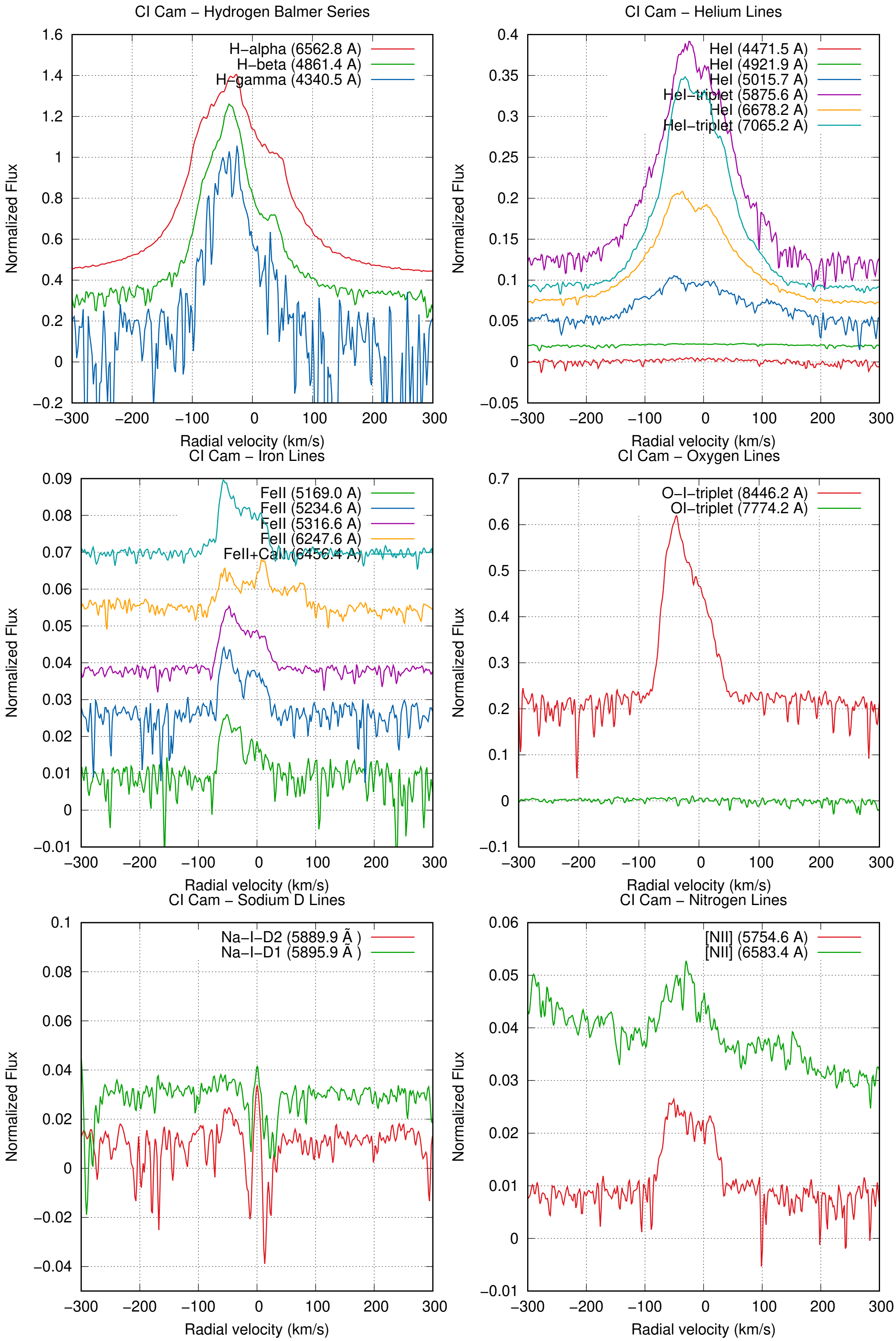

FIGURE 4 Profiles of various atomic lines in the spectrum of CI Cam. Top row: Balmer hydrogen lines (left) and helium lines (right). Middle row: Iron lines (left) and oxygen lines (right). Bottom row: Sodium lines showing both interstellar absorption and circumstellar emission components (left), and forbidden nitrogen lines (right).

TABLE 1 Identification of spectral lines and derived radial velocities

λ_{obs} (Å)	Id.	λ_{lab} (Å)	v_r (km/s)	Note
8445.516	O I	8446.359	−29.9	Oxygen triplet (fluorescent)
7710.958	Fe II	7711.720	−29.7	Iron
7280.778	Fe II	7281.349	−23.5	Iron (or [Ca II])
7064.816	He I	7065.190	−15.9	Strong helium emission line
6677.686	He I	6678.152	−20.9	Strong helium emission line
6562.112	Hα	6562.817	−32.2	Strongest hydrogen line
6582.976	[N II]	6583.450	−21.6	Forbidden nitrogen line
6455.651	Fe II	6456.383	−34.0	Iron (multiplet 74)
6346.501	Fe II	6347.110	−28.8	Iron (multiplet 40)
6317.433	Fe II	6317.986	−26.3	Iron (multiplet 74)
6247.594	Fe II	6247.557	+1.8	Iron (multiplet 74)
6238.229	Fe II	6238.392	−7.8	Iron (multiplet 74)
6124.496	Fe II	6124.893	−19.4	Iron
5875.312	He I	5875.621	−15.7	Strong helium emission line
5754.092	[N II]	5754.590	−25.9	Forbidden nitrogen line
5577.345	[O I]	5577.339	+0.3	Telluric oxygen line
5534.262	Fe II	5534.847	−31.7	Iron (multiplet 55)
5316.084	Fe II	5316.615	−30.0	Iron (multiplet 49)
5015.440	He I	5015.678	−14.2	Helium
4860.773	Hβ	4861.333	−34.5	Balmer hydrogen line

4 | DISCUSSION

4.1 | Model of the CI Cam System

Based on our observations and data from the literature, we propose the following model for the CI Cam system:

1. **Central B star** of type B0-B2 III with a mass of 12-22 $M_\odot$.
2. **Stratified circumstellar disk** around the primary star:
    - Inner hot region (up to ∼30 $R_\odot$) - source of He I emissions
    - Middle region (30-100 $R_\odot$) - periodically disturbed by the passage of the compact component
    - Outer cooler region (above 100 $R_\odot$) - source of Fe II emissions
    - Dust component (up to 38 AU) - observable in IR
3. **Compact component** (likely a white dwarf with a mass of ∼1 $M_\odot$) on an eccentric orbit that is not coplanar with the disk plane. This geometry allows the compact component to pass through the disk only at certain points in its orbit, while most of the time it moves above or below the disk plane.

The asymmetry in the emission profiles of Fe II lines (V/R > 1) is likely caused by spiral density waves in the disk, which are induced by the gravitational effect of the compact component during regular passages through periastron. These spiral structures cause systematically higher density in parts of the disk that are approaching the observer.

The outburst from 1998 can be interpreted as a thermonuclear explosion of hydrogen accumulated on the surface of the white dwarf as a result of accretion from the disk of the primary star. An alternative explanation could be an episode of enhanced accretion onto a neutron star.

4.2 | Comparison with Previous Studies

Our findings are generally consistent with previous studies of CI Cam, particularly regarding the presence of a stratified circumstellar environment and the existence of a binary system with a compact companion. However, there are some notable differences and new insights.

The radial velocities measured in our spectrum are significantly less negative than those reported in some earlier studies. For instance, the forbidden [N II] line in our data gives a systemic velocity of approximately -25 km/s, while Klochkova et al. (6) report -55.4 ± 0.6 km/s. This discrepancy can be explained if our observations happened to catch the system at a specific orbital phase where the disk component is receding from us.

The presence of the O I 8446Å line with the simultaneous absence of the O I 7771-7775Å triplet confirms the Lyman-β

fluorescence mechanism, which has been reported in previous studies of similar systems but has not been extensively discussed for CI Cam specifically.

The detection of a distinct plateau-like structure at around +50 km/s in the Hα profile, which is not present in archival data, suggests transient phenomena in the system that might be related to the orbital motion of the compact companion or episodes of enhanced mass transfer.

4.3 | Implications for the Nature of the Compact Object

The nature of the compact object in CI Cam remains a subject of debate. The 1998 outburst has been interpreted either as a thermonuclear explosion on the surface of a white dwarf (similar to a classical nova) or as an episode of enhanced accretion onto a neutron star or black hole (similar to an X-ray transient).

Our observations do not definitively determine the nature of the compact object, but they do provide some constraints. The range of radial velocity variations observed across different epochs (approximately 25 km/s) is consistent with the expected orbital motion of the primary component in a system where the companion has a mass of 1-2 $M_{\odot}$. This mass range is compatible with either a white dwarf or a neutron star.

The presence of strong emission lines and evidence for a disturbed disk suggests ongoing interaction between the compact object and the circumstellar material. The complex profiles of hydrogen and helium lines, in particular, may reflect the influence of the compact object's gravitational field on the disk structure.

5 | CONCLUSIONS

High-resolution spectroscopic observations of CI Cam with the Ondřejov Echelle Spectrograph have provided valuable insights into the physical conditions and kinematics of this unique binary system. The stratification of emission regions revealed by different velocity profiles of various elements presents strong evidence for temperature and density gradients in the circumstellar disk. The asymmetries in emission profiles suggest the presence of long-term stable spiral structures, which are likely a consequence of the gravitational influence of the compact component.

The key findings of our study include:

1. The emission line profiles show a clear stratification, with different elements originating from regions at different distances from the central star.

2. The radial velocities of most emission lines in our spectrum are around -25 km/s, which is less negative than values reported in earlier observations, suggesting orbital motion of the system components.

3. The strong O I 8446 Åemission line, coupled with the absence of the O I 7771-7775Å triplet, indicates Lyman-β fluorescence as the dominant excitation mechanism.

4. The Hα profile exhibits a unique plateau-like structure at around +50 km/s that is not present in archival spectra, suggesting transient phenomena in the system.

5. The forbidden [N II] lines provide a measure of the systemic velocity that differs from previously published values, which may be due to orbital phase effects.

For further progress in understanding this fascinating system, it would be valuable to obtain a time series of spectra covering the entire orbital period. This would allow us to systematically monitor how spectral characteristics change with orbital phase and more precisely determine which properties are a direct consequence of interaction with the compact component. CI Cam thus remains one of the most interesting objects for studying interactions in close binaries and for testing models of stellar evolution in binary systems.

ACKNOWLEDGMENTS

We thank the staff of the Astronomical Institute of the Czech Academy of Sciences in Ondřejov for their support during the observations. B.N. acknowledges support from her high school supervisor, M.P. This work made use of the IRAF software provided by the National Optical Astronomy Observatory.

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How cite this article: Jelínek M., Nohová B. (2025), Spectroscopic observations of CI Camelopardalis: Evidence for stratified circumstellar environment and variable radial velocities, *Astron. Nachr.*, *2025;00:1–9*.