Research Square

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The He I 5876 LINE in the Spectra of Herbig Ae Stars

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Research Article

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Abstract

We present the results of observations of the neutral helium He I 5876 line in the spectra of four Herbig Ae stars. High-resolution spectral observations (R = 20000) were carried out between 1995 and 2025 at the Crimean Astrophysical Observatory using the 2.6 m ZTSh telescope at the Coudé focus.

One of the program stars, CQ Tau, belongs to the UX Ori type stars, which are characterized by strong photopolarimetric activity and spectroscopic signatures of accretion. The other three stars have an intermediate orientation of their circumstellar disks. Two of them (AB Aur, HD 190073) show spectroscopic signatures of mass outflow, and HD 141569 is known as a young star whose protoplanetary disk is more evolved than those of other Herbig Ae stars. Thus, the observational data make it possible to analyze the variability of the helium line He I 5876 in stars with different orientations of circumstellar disks and at different stages of the planet formation process.

The results of spectral observations showed that the analysis of the variability of the He I 5876 line may be useful for researching of Herbig Ae stars. It allows to study the inner regions of circumstellar gas envelopes, the kinematic and physical parameters of circumstellar matter and the processes running in the young protoplanetary systems.

1 Introduction

Herbig Ae stars are well known as young, intermediate-mass objects that have not yet reached the main sequence and are surrounded by extensive gas-and-dust discs in which active planet formation processes are taking place. The inner regions of these discs are free of dust – this is where accretion of circumstellar (CS) material onto the star takes place, while at higher latitudes gas outflow (wind) is observed. This accounts for the observed connection between the character of activity of young stars and their orientation relative to the observer [1]. Stars oriented at intermediate angles are characterized by weak photometric variability and spectroscopic signatures of outflow. When the disk orientation is closer to edge-on (UX Ori type stars), matter of the accretion disk intersects the line of sight. This causes strong photopolarimetric activity and signs of accretion in the spectrum.

The optical spectra of young stars are characterised by the presence of circumstellar emission lines, primarily the first members of the hydrogen Balmer series, as well as metals, first of all the sodium resonance doublet lines, iron, etc. A special place among them is occupied by the neutral helium He I 5876 line. Modeling by Tambovtseva et al. [2] has shown that this line is formed in the inner region of the accretion disk, in a compact hot zone where the temperature can reach 17000˚ K and higher, for example, inside stellar magnetospheres. And although the question of the presence of magnetic fields in young stars is still under discussion, the presence of compact magnetospheres in Herbig Ae stars is confirmed by observational data (see, e.g., [3–5]).

The neutral helium line He I 5876 allows detailed study of the immediate vicinity of the star, revealing changes in the physical and kinematic properties of CS gas in the region where the accretion disk

interacts with the magnetosphere and where the wind is formed. The helium line is also of interest for estimating the accretion rate in young stars (see [2]). We also know that the accretion rate can change in the presence of a low-mass companion or planet on a timescale equal to the orbital period (see, e.g., [6]). Therefore, monitoring changes in the He I 5876 line is of great interest in solving various problems.

This paper presents the results of spectral monitoring in the region of the helium line He I 5876 for four Herbig Ae stars. One of them, CQ Tau, belongs to the UX Ori type stars and spectral signs of accretion together with strong photopolarimetric variability. The other stars have an intermediate orientation of their CS disks. Two of them (HD 190073 and AB Aur) show spectral signs of outflow. The star HD 141569 should be noted separately. Its spectrum is distinguished by greater stability, showing only weak variability of the emission profiles of CS lines (see [7]). Such stability indicates that the material in the inner region of the disk has been significantly processed during planet formation compared to other young stars. This is confirmed by the detection [8] of an extended belt of width 0.3 a.u. at a distance of 1 a.u., consisting of small bodies with mass around 1.4×10^{-8} $M_{\oplus}$. Thus, the inclusion of HD 141569 in this work allows us to trace the character of variability of the He I 5876 line not only in stars with different disk orientations, but also at different stages of the planet formation process.

2 Observations

High-resolution spectral observations (R = 20000) were carried out at the Crimean Astrophysical Observatory (CrAO) with the 2.6 m ZTSh telescope in the period from 1995 to 2025. It should be noted that until 2013 all spectra were obtained using a coudé spectrograph equipped with a CCD camera. Since late 2013 an echelle spectrograph has been installed at the coudé focus, which made it possible to significantly expand the investigated spectral range. The two-dimensional images were processed using the DECH software package developed by G.A. Galazutdinov. Further processing of the obtained spectral orders (normalization to the continuum level, wavelength calibration, reduction to the barycenter, correction for telluric lines, etc.) was performed with the SPE software package developed by S.G. Sergeev and used at CrAO. The error in determining the equivalent width *EW(He I)* for most dates does not exceed 0.05 Å.

In total, 26 spectra for CQ Tau, 90 spectra for HD 190073, 33 spectra for HD 36112, 75 spectra for AB Aur, and 8 spectra for HD 141569 were obtained in the region of the Na I D and He I 5876 lines.

3 Results

3.1 CQ Tau

CQ Tau belongs to the small group of UX Ori type stars, whose CS disk orientation is close to the "edge-on" position, which causes strong photopolarimetric activity of these stars and spectral signs of accretion [1]. In work [9], the long-term photometric and polarimetric variability of the star was studied in detail, and it was shown that in addition to the random component typical for UX Ori type stars, the

brightness variations contain a powerful periodic component with a period of about 10 years. This provided grounds for assuming that the star has a low-mass companion.

Our results of simultaneous spectral and photometric monitoring of this star, performed at CrAO, were published earlier in [10]. Spectra were obtained in the region of the Hα emission line and the resonance doublet lines of sodium Na I D. The variability of the helium line He I 5876 was not analyzed in that paper; this analysis is presented here for the first time.

Figure 1 shows the averaged profile of the He I 5876 line and, for comparison, the average profiles of the Na I D sodium resonance doublet and the Hα emission line (due to the difference in scale, the figure shows not the entire Hα profile, but the broad emission wings). All these lines are formed in the accretion disk of the star, so the boundaries of their emission profiles are close to each other. They have an inverse P Cyg profile characteristic of accreting gas; the accretion velocity can reach + 300 km/s and more. Such profiles are typical for UX Ori type stars. For the analysis of He I variability the same parameters were chosen as in work [10]. These are the radial velocity of the absorption component V_{abs} and the red edge of the absorption V_{red} (determined at the intensity level I = 0.8). Figure 2a shows the variation of these parameters for helium (two upper panels) and, for comparison, for the sodium resonance doublet lines (two lower panels).

It is clearly seen that the variability of V_{abs} and V_{red}, for both helium and sodium, occurs on a timescale of about 700^{d}: the radial velocities first increase sharply and then return to their usual values. It is interesting that the amplitude of the helium line variability gradually decreases, demonstrating another long-term variability. From [10] it follows that this variability is in good agreement with the photometric activity of the star: at J.D. 2450000 the star was at minimum (V ~ 11m), then the brightness began to increase, and between J.D. 2451000 and 2452000 the star was in a bright state (V ~ 9m). Similar changes are also noted in the Hα line, but its emission profile shows not one but two red-shifted absorption components. The low-velocity component (V I ≤ 100 km/s) is quite stable and shows slow variations on a multi-year timescale; it was associated with the accretion disk of the star itself. The high-velocity component (V II > 100 km/s), on the contrary, demonstrates very strong variability in radial velocity. The timescale of variability is about ~ 700 days.

Figure 2b shows a comparison of the variability of V_{abs}*(He I)* and V_{abs}*(Na I)*. We see that sodium also has two distinguishable absorption components: the low-velocity component I (V_{abs} ≤ 60 km/s) does not depend on V_{abs}*(He I)*, while the high-velocity component II (V_{abs} > 60 km/s) shows an increase in values together with the radial velocity V_{abs}*(He I)*. Apparently, in the helium line there is no clear separation into two absorption components; they are merged into a single broad absorption, in which the variable high-velocity absorption component plays the main role.

Thus, we see in the Hα, Na I D, and He I 5876 lines the appearance on the line of sight of CS gas whose kinematics differ from the kinematics of the surrounding accretion disk. In work [10], thanks to photometric support of spectral observations, the appearance of such gas was able to be linked to the

dissipation of comet-like bodies. It became clear that there is a physical mechanism that perturbs the motion of these bodies on a timescale of 700 days, drawing them into the inner region of the disk. There, moving in highly elongated orbits, they approach close to the star and dissipate, supplying gas with completely different kinematics to the immediate vicinity of the star. In [10] it was suggested that a low-mass companion or planet could act as such a mechanism.

3.2 HD 190073

This unusual Herbig Ae star is distinguished by a very strong emission spectrum, which includes lines of hydrogen, helium, the resonance doublet of sodium, and others (see works [4], [11–12]). The emission profiles are of P Cyg type with a blue-shifted absorption component, which is a sign of dense outflowing gas on the line of sight.

Another distinctive feature of the star is a very low projection of the rotation velocity *Vsini* (according to [12] it is 3.19 km/s). Such a combination of very small *Vsini* and signs of wind on the line of sight may indicate that the inclination angle of the CS disk of the star differs little from the "pole-on" position. In [13] an estimate of i < 20° is given; more precise determinations of the inclination angle have not yet been made. Study of the CS disk of HD 190073 [14] shows that active planet formation is taking place in it.

The spectral variability of this star was analyzed by us earlier in work [11], where results obtained in the period from 2009 to 2017 are presented. They showed that both the helium line and the sodium resonance doublet lines demonstrate multi-year wave-like variability, but it was unclear how much it repeats, whether it is cyclical. In the present work, the variability of the helium line is considered for the period from 2009 to 2025, which is twice as long as the time interval analyzed in work [11].

Figure 3 presents the averaged profiles of Hα, Na I D, and He I 5876 lines superimposed on one another. It is clearly seen that the Hα emission line (shown by dots) demonstrates a P Cyg profile characteristic of matter outflow. The profile of the Hα emission are much wider than those of the Na I D and He I 5876 lines, which is in good agreement with the star's orientation, when the wind region is located on the line of sight. At the same time, helium and the sodium resonance doublet are formed in the region of the stellar magnetosphere and accretion disk, so the boundaries of their emission profiles are close to each other and amount to ± 200 km/s. The helium line itself has the appearance of a single emission without any signs of absorption on the blue and red sides. The exception is weak absorption in the center of the profile. It is observed every night and shows no noticeable variability, and its width is twice the instrumental profile width.

For analysis of helium line variability, the following parameters were selected: the equivalent width of emission *EW*, its intensity *I*, as well as the blue edge of the emission profile at 30% of the maximum intensity $V_{blue}(30\%)$, and the emission width at this level $W_{em}(30\%)$. Their changes are shown in Fig. 4a. It is clearly seen that all of them describe cyclical variability on a timescale of about 2000^{d}.

An interesting feature is that each cycle may be traced more or less distinctly. When the emission intensity reaches a maximum, the emission line becomes narrower, and at minimum it becomes wider. Figure 4b shows a comparison of equivalent widths of sodium and helium lines. They show good agreement with each other. Overall, the variability of the helium line repeats the variability of Hα and Na I D (see [11]).

3.3 AB Aur

AB Aur is the brightest and most well-known Herbig Ae star. Its spectrum contains many emission lines formed in the circumstellar gas envelope. The most prominent of these are the first members of the Balmer series, as well as lines of FeII, CaII, HeI, NaI, and others [15–16]. The star is surrounded by a gas-and-dust disk, which according to interferometric observations [17–18] has a complex asymmetric structure with spiral arms, contains at least two separate rings with different inclinations to the line of sight. All these facts suggest that a young planetary system is forming within the CS disc of AB Aur.

Estimates of the inclination angle of the stellar rotation axis to the line of sight may differ in the works of different authors. Observations of the CS disk at ALMA [19] give values i ~ 23°. Such an inclination angle indicates intermediate orientation, which is confirmed by P Cyg profiles of the Balmer emission lines in the spectrum of AB Aur. Results of Hα-interferometric observations [20] show the presence of a compact magnetosphere at the star at a distance r ≤ 0.04 a.u.

Figure 5 shows averaged profiles of Hα, Na I D, and He I 5876 superimposed on each other. It is clearly seen that the emission line Hα (shown by dots) demonstrates a P Cyg profile characteristic of matter outflow. As it is formed in the wind region, the boundaries of the Hα emission are broad and amount to ± 500 km/s.

In contrast, the helium He I line and the sodium resonance doublet Na I D are formed in the stellar magnetosphere and the accretion disk, therefore their emission profiles are narrower. The emission wing boundaries are ± 100 km/s for the sodium resonance doublet and ± 200 km/s for helium. It is interesting that the He I 5876 line shows not a single emission, like HD 190073, but an inverse P Cyg profile indicating the presence of accreting gas between the star and the observer. It is also unusual that on some nights not one but two absorption components were observed. This made it possible to distinguish the low-velocity component I (V_{abs} < 100 km/s), which is always present in the stellar spectrum, and the high-velocity component II (V_{abs} > 100 km/s), which is observed only on certain nights.

For the analysis of He I line variability the following parameters were chosen: the emission equivalent width *EW*, its intensity *I*, and the radial velocity of the absorption components V_{abs}. Their variation is shown in Fig. 6a. The two absorptions are shown by different symbols (black circles indicate the low-velocity component I, open circles indicate the high-velocity component II).

As can be seen from the figure, the parameters of the He I 5876 line show complex variability in which a multi-year wave can be noticed. It is traced both in the variation of *EW* and in the variability of *I* and V_{abs}: when *EW* and *I* reach maximum values, the low-velocity component shows minimum accretion velocities. However, we do not yet know whether this variability is cyclical.

Comparison of radial velocities of absorption components as a function of the emission intensity of helium *I(He I)* and the resonance doublet of sodium *I(Na I)* is shown in Fig. 6b. It shows that the radial velocity V_{abs} of the low-velocity component (black circles) demonstrates the connection with the intensity of the helium emission line *I(He I)*, while the radial velocity variability of the high-velocity component II (open circles) does not depend on the helium intensity change. On the other hand, component II shows the connection with changing of the intensity of the sodium resonance doublet *I(Na I)*, while the low-velocity component does not show such connection.

This result indicates that the physical mechanism responsible for the formation of the high-velocity absorption component II is external with respect to the helium line. It is related to processes occurring in a more distant region of the CS gas envelope, where the CS emission of the resonance doublet is formed. This is the accretion disk of the star. Apparently, in the helium line we see the same process as in CQ Tau – the appearance in the immediate vicinity of the star of gas with a completely different kinematics, caused by the dissipation of small bodies orbiting the star in highly elongated orbits.

Thus, in the CS disk of AB Aur we observe the same processes as in the disk of CQ Tau, but from a different viewing angle.

3.4 HD 141569

The Herbig Ae star HD 141569 is one of the nearest young stars to us (d = 112 pc according to [21]). Its CS disk has a complex structure consisting of many rings, caused by the presence of invisible companions.

In spectral terms, the star has been studied weaker. The Hα line always shows a two-component emission profile, which changes weakly on a multi-year timescale [7]. CS lines are weaker than those of most Herbig Ae/Be stars. In [5], it is shown that the region of formation of the Hα emission line is very compact and does not exceed 0.12 a.u. Moreover, the magnetospheric accretion model does not apply to HD 141569 because of the too rapid rotation of the star. It is interesting that the helium line He I 5876 was not observed in [7]. The results of our observations also show that the helium line in the spectrum of HD 141569 is often absent.

Figure 7 shows two extreme types of profiles of the helium line He I 5876 and the sodium resonance doublet Na I D observed in the star. In the first case there is nothing at the position of He I 5876, and only narrow interstellar absorptions are seen in the sodium lines. In the second case a weak absorption line without any signs of emission is seen at the position of helium, indicating gas accretion with velocities of about + 300 km/s (very weak signs of gas outflow can be seen in the Na I D resonance doublet lines at

this moment). All other profiles observed in this star are placed between these two types of spectra, so we do not present them here.

4 Discussion

The results of spectral observations show unusual behavior of the observed profiles of the He I 5876 line. Several factors affect it, the most significant of which is the orientation of the CS disk of the star relative to the observer. In UX Ori type stars we observe the material from the accretion disk on the line of sight; therefore, in the case of CQ Tau, the helium line demonstrates an inverse P Cyg profile, characteristic of gas accretion with velocities up to + 300 km/s and higher. The variability of He I 5876 in this case reproduces the result obtained for the sodium resonance doublet Na I D and Hα in [10]. It consists in the fact that gas with unusual kinematic parameters, differing from the kinematics of the accretion disk, was detected in the immediate vicinity of the star. There is every reason to believe that this gas is the result of dissipation of small bodies (planetesimals), whose orbits are periodically perturbed by a more massive object, which may be a gas giant or a low-mass companion. Data [9, 23] are in good agreement with this conclusion.

The results of observations obtained for another Herbig Ae star, AB Aur, turned out to be even more unexpected. Two red-shifted absorption components in the He I 5876 line were detected not in a UX Ori type star, but in a star with intermediate disk orientation. In the Hα emission line, AB Aur shows signs of matter outflow; in the resonance doublet lines of sodium, signs of outflow may coexist with signs of accretion. But in the helium line, we always observe an inverse P Cyg profile and two absorption components, one of which is always present and shows very weak radial velocity variability from night to night, while the other is observed only during certain periods of time and shows rapid velocity changes.

How does this happen? Data [18] show that AB Aur has a compact magnetosphere. With intermediate star orientation, the line of sight crosses not only the wind, where the main part of the Hα emission profile is formed, but also the magnetosphere, in which the He I 5876 line is formed. Since the gas at the line of sight inside this region moves toward the star, this explains the inverse P Cyg profiles observed in the helium line and the appearance of a red-shifted low-velocity absorption component I.

For the formation of the high-velocity absorption component II, indicating the presence on the line of sight of gas with a completely different kinematics, the described mechanism is not sufficient. The anomalous velocities demonstrated by the high-velocity component of helium He I like the case of CQ Tau. So they may be also explained by the dissipation of small bodies (planetesimals) moving in highly elongated orbits. The connection observed between the variation of the high-velocity component and the intensity of the sodium resonance doublet lines is in good agreement with this assumption. In this case AB Aur can be considered as an analog of CQ Tau, but observed from a different angle. Unfortunately, we do not yet have data on the periodicity of appearance of this high-velocity component, so the question of the nature of such unusual activity remains open.

Another star with intermediate orientation, HD 190073, also showed unusual behavior of He I 5876. This line has a single emission profile without any signs of absorption components, except for weak central absorption. In [3], it is shown that the star has a compact magnetosphere, the size of which is 3 R_*. At the same time, the angle between the rotation axis of HD 190073 and the dipole axis is close to 90˚. Given the very low values of the rotation velocity projection of this star and estimates of the inclination angle of the rotation axis to the observer, one can suppose that the star's orientation is rather close to the "pole-on" position. Then the absence of blue or red-shifted absorption lines in He I can be explained by the fact that at such an orientation, the magnetosphere projects onto the star only in the polar region, where magnetic field lines are almost perpendicular to the line of sight. In this case, one would expect only weak absorption to appear in the helium line, whose radial velocity would be close to the star's radial velocity. Apparently, the central absorption in the He I emission profile has precisely such a nature. Thus, the character of multi-year variability of the parameters of the He I 5876 emission line makes it possible to suggest the existence of activity cycles in the star with a characteristic timescale of about 2000 days. In this context, the highest values of *EW* and *I* correspond to the minimum values of the emission width $W_{em}(30\%)$, and vice versa. In fact, we observe how the emission profile on a 2000^d timescale becomes either narrower and higher, or wider and flatter. Since the He I 5876 emission is formed in the magnetosphere, this result can be interpreted within the framework of the model of interaction between the stellar magnetosphere and the accretion disk. The magnetic field truncates the accretion disk, stopping Keplerian rotation; meanwhile, the disk, in turn, constantly pushes on the magnetosphere boundary. The result of this interaction will depend greatly on the mass accretion rate. The fact that in HD 190073 this rate is not constant but changes cyclically follows from the founded variability of the helium emission line parameters.

It should be noted that the change of accretion rate in young protoplanetary disks is an expected process, since forming planets actively affect disk accretion [5].

A special case is represented by the star HD 141569. In work [8], it is noted that this is the only pre-main-sequence star in which a hybrid disk has been founded. This means that the planet formation process has progressed further than in other young stars. The dust has already been significantly processed, and the disk itself represents a complex system of multiple rings of various sizes [22]. One of such rings, according to [8], represents gas with Keplerian rotation at a distance of 0.09 a.u. Analysis of IR emission of the star showed another ring of width 0.3 a.u. at a distance of 1 a.u., consisting of small bodies ($m \sim 1.4\times10^{-8}\ M_\oplus$).

Under these conditions, the spectrum of HD 141569 shows only weak variability. We can see in the helium line, complete absence of the CS emission component and only small variable absorption, which often completely disappears. Thus, we can conclude that there is no steady-state gas accretion in the inner regions of the CS disc. The individual accretion events we have observed are apparently random events, such as dissipation of small bodies or planetesimals, which may approach the star closely as a result of orbital perturbations (such scenarios are predicted by modern theories of planet formation, for example, [24]).

5 Conclusion

The observational results showed that the analysis of the variability of the He I 5876 line represents an original research method, allowing one to probe the inner regions of CS gas envelopes, including the stellar magnetosphere and the *surrounding* region of the accretion disk, to study the kinematic and physical parameters of CS gas, and to relate them to processes occurring in young protoplanetary systems. The following conclusions have been obtained:

- observational data confirmed that the He I 5876 line is a good indicator of accretion activity in young hot stars;

- the He I 5876 profiles observed in the spectra of the program stars depend not only on the orientation of CS disks, but also on the magnetosphere parameters of the star (radius, inclination of the magnetic field relative to the star's rotation axis, etc.);

- the case when He I 5876 shows an accretion-type profile is of special interest for investigation, as it allows revealing changes in the kinematic parameters of gas accreting onto the star and detecting the appearance on the line of sight of material whose kinematics differ from that of the accretion disk; such phenomena may be related to the dissipation of comet-like bodies or planetesimals;

- study of the long-term variability of He I 5876 allows revealing possible cyclical changes in emission parameters caused by changes in the accretion rate; such changes are expected and follow from the results of modeling young protoplanetary disks.

- the case of the hybrid disk around the star HD 141569 showed that as the system evolves, the accretion activity of protoplanetary disks decreases, and the helium line essentially disappears. Residual activity can be explained within the framework of the theory of formation and evolution of planetesimal.

Declarations

Author Contribution

The entire article is written by O.V. Kozlova.

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Figures

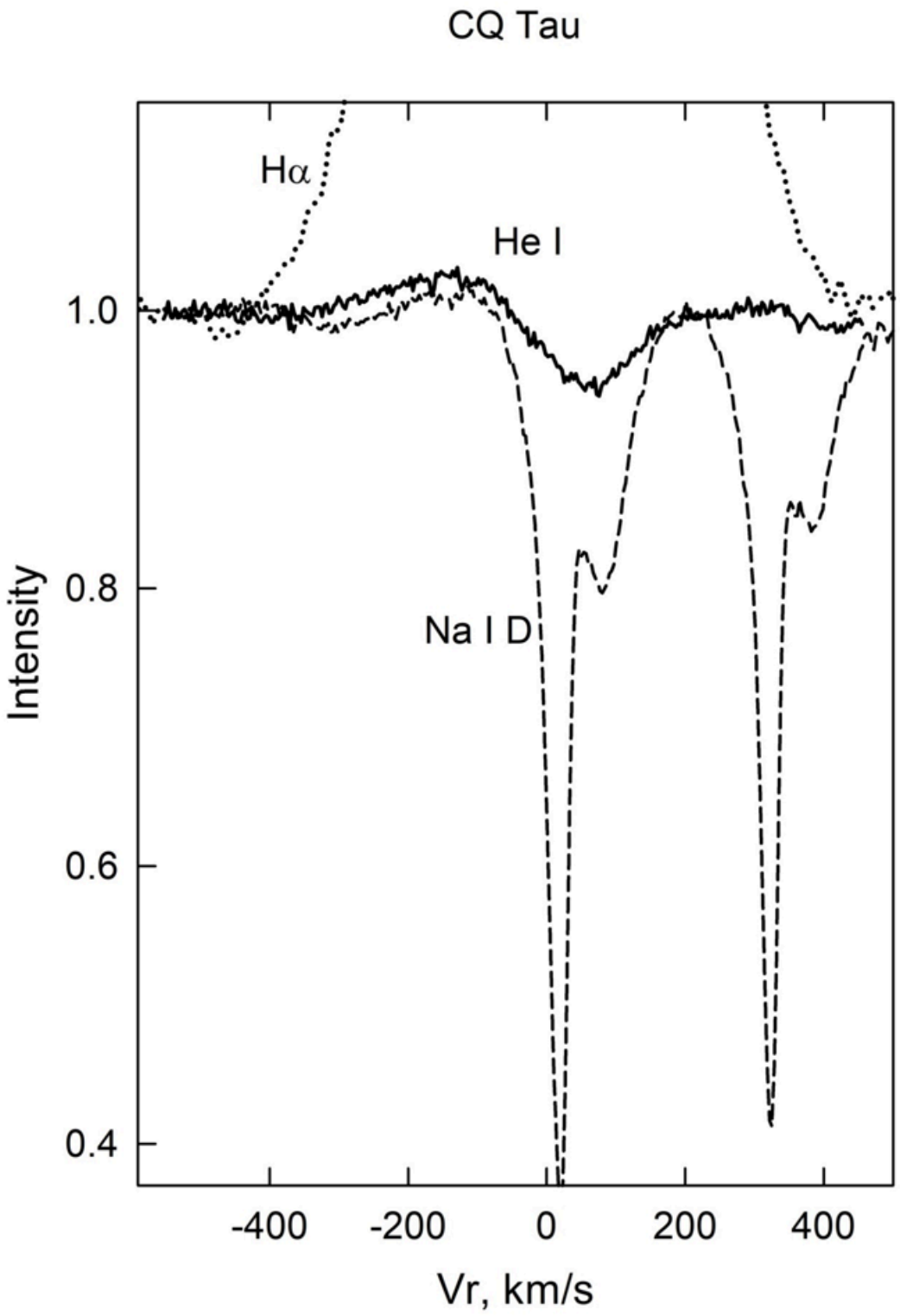


Figure 1

The averaged Hα (shown by dots), Na I D (dashed line), and He I 5876 (solid line) profiles superimposed on each other for CQ Tau.

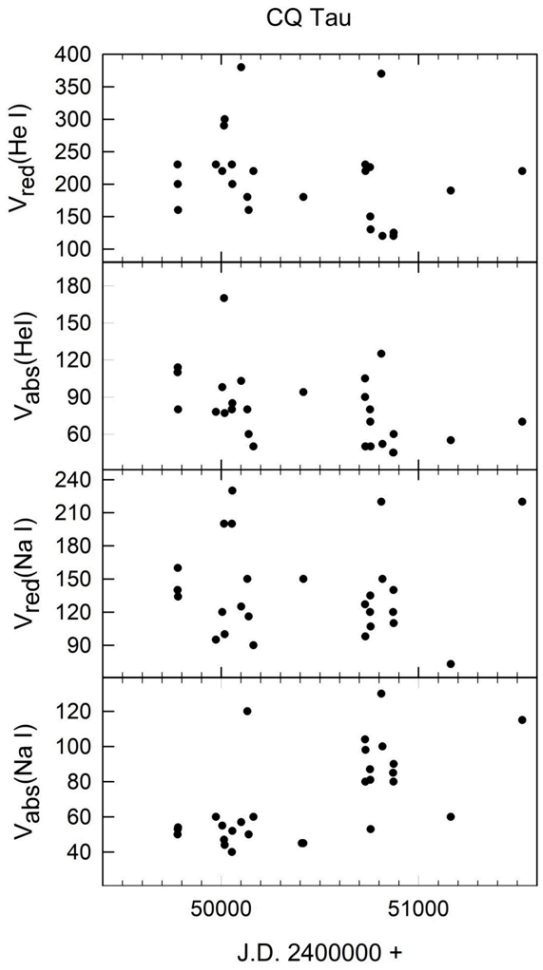


Figure 2a.

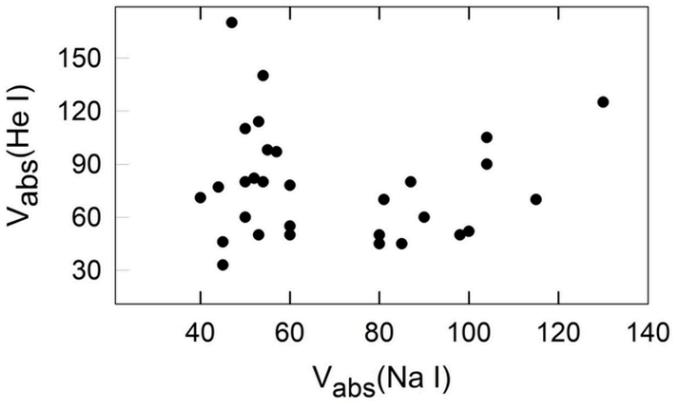


Figure 2b.

Figure 2

a. Variation of the radial velocity of the absorption component V_{abs} and the red edge of the absorption V_{red} for helium (two upper panels) and, for comparison, for the sodium resonance doublet lines (two lower panels) for CQ Tau.

b. Comparison of the variability of V_{abs}(He I) and V_{abs}(Na I) for CQ Tau.

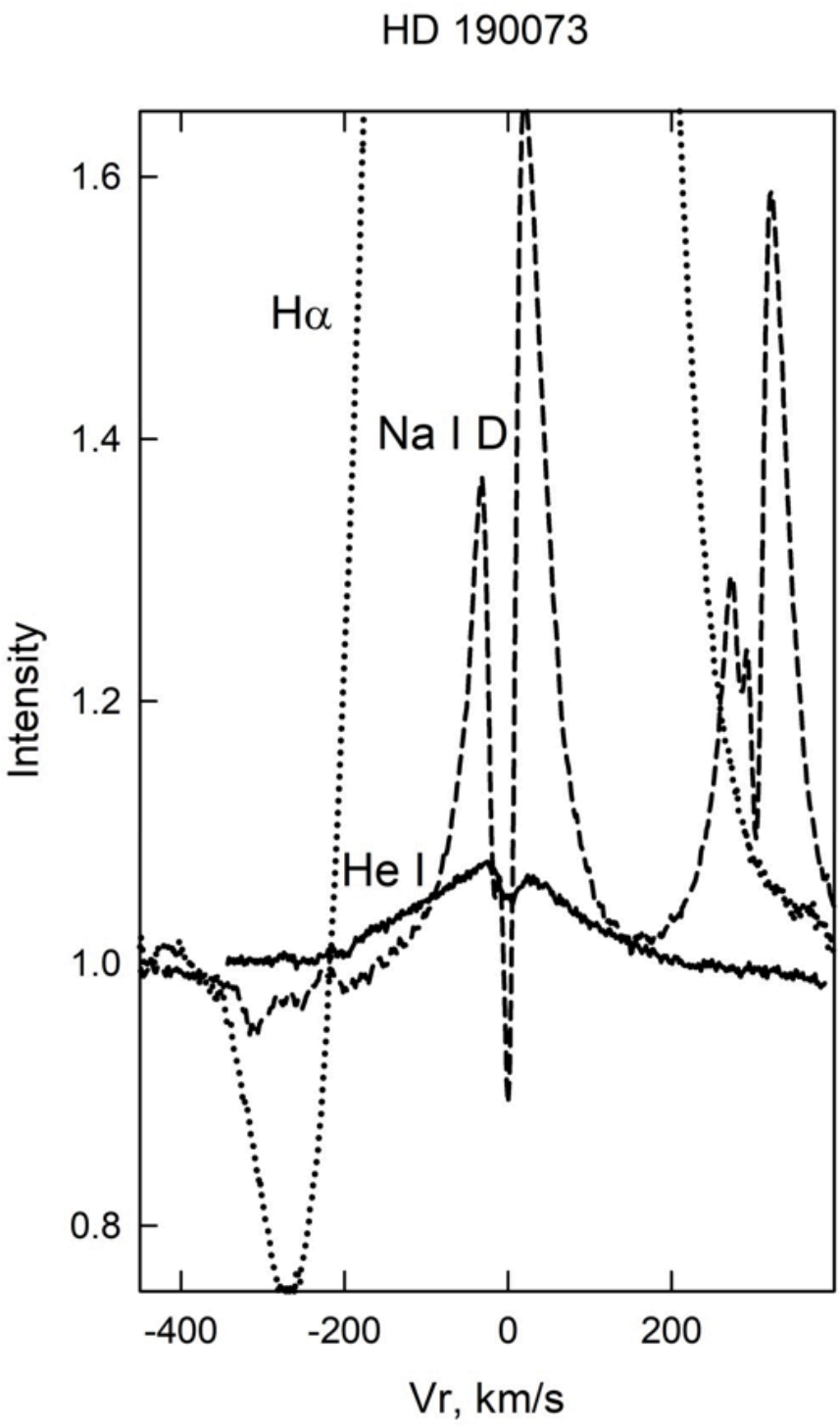


Figure 3

The averaged Hα (shown by dots), Na I D (dashed line), and He I 5876 (solid line) profiles superimposed on each other for HD 190073.

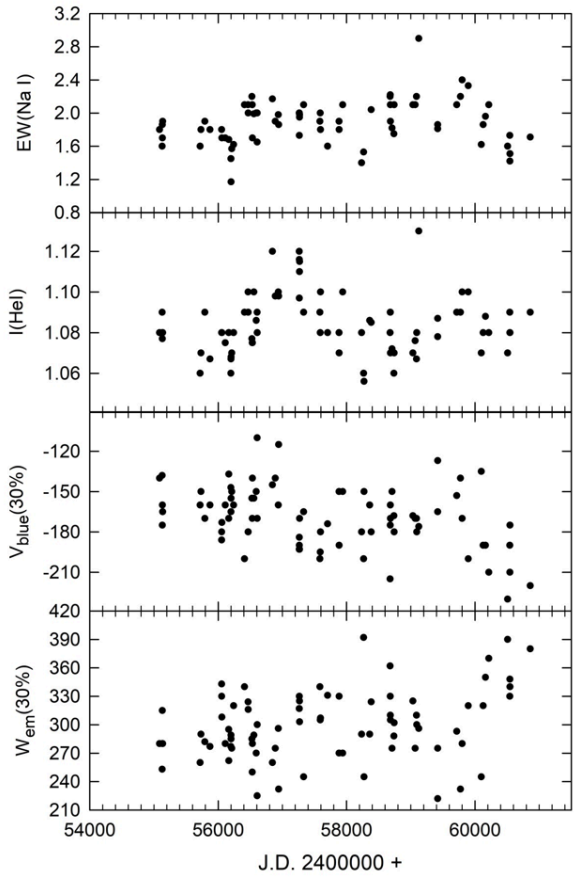


Figure 4a.

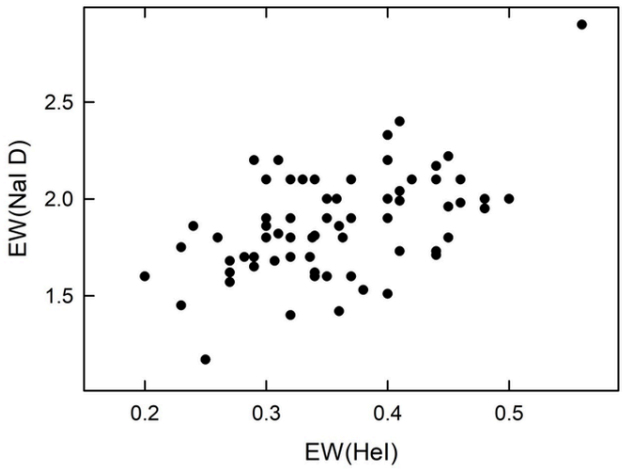


Figure 4b.

Figure 4

a. Variability of the emission equivalent width EW, its intensity I, as well as the blue edge of the emission profile at the level of 30% of the maximum intensity V_{blue}(30%) and the emission width at this level W_{em}(30%) for HD 190073.

b. Comparison of the equivalent widths of sodium EW(Na I) and helium EW(He I).

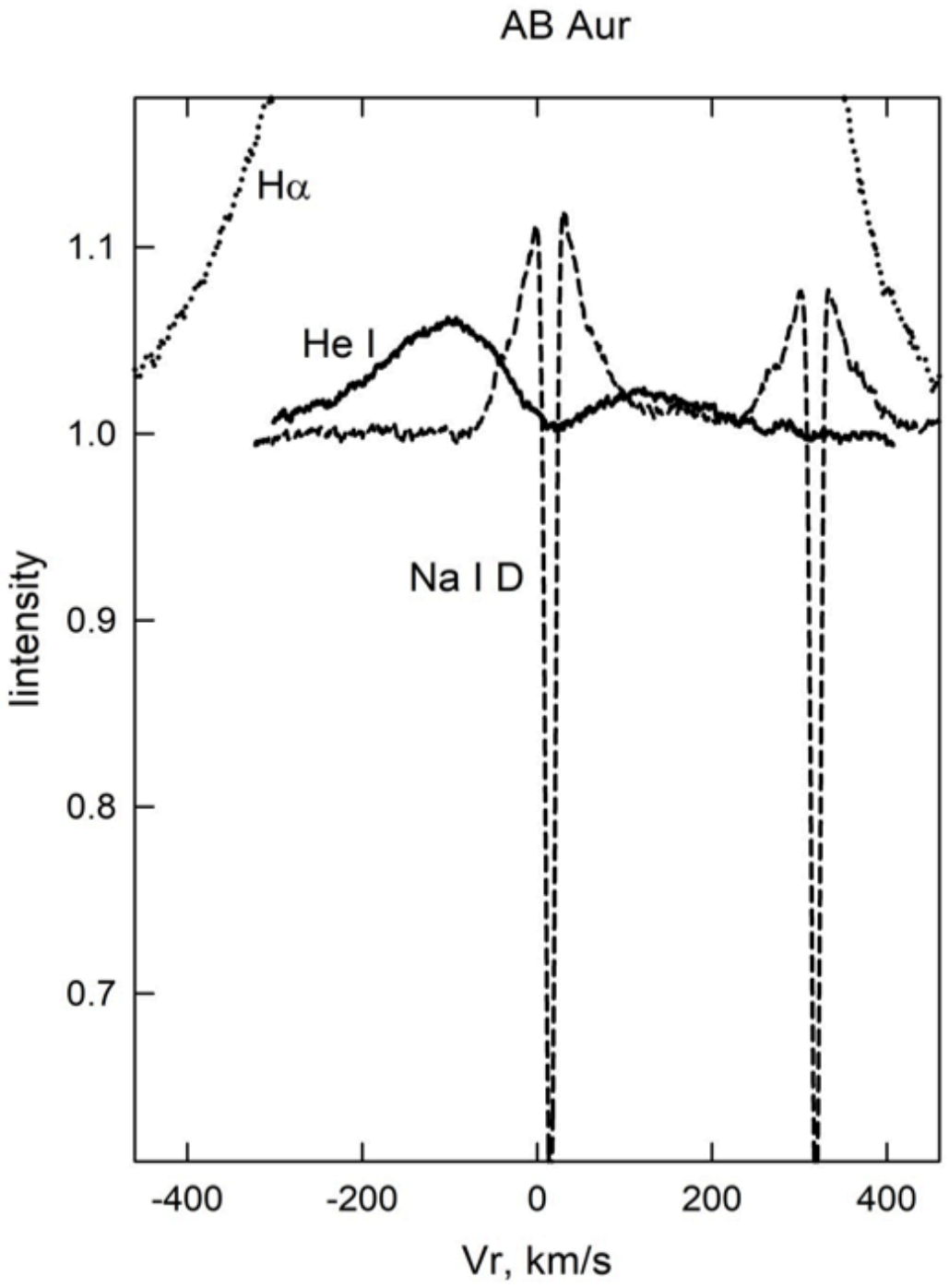


Figure 5

The averaged Hα (shown by dots), Na I D (dashed line), and He I 5876 (solid line) profiles superimposed on each other for AB Aur.

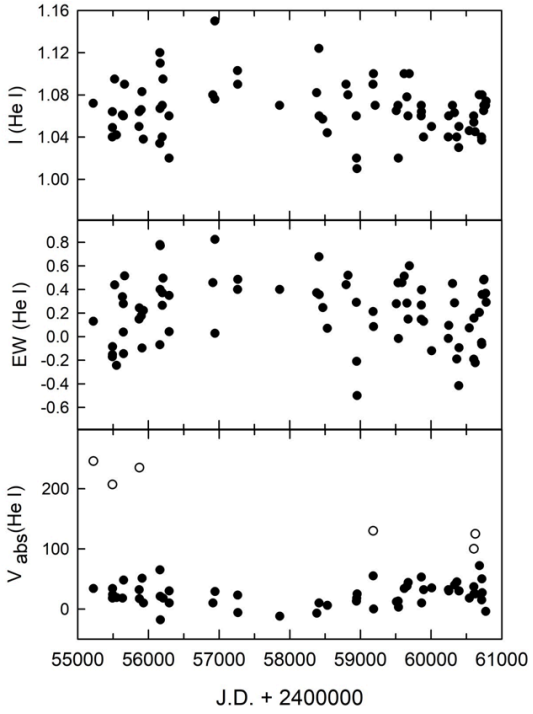


Figure 6a.

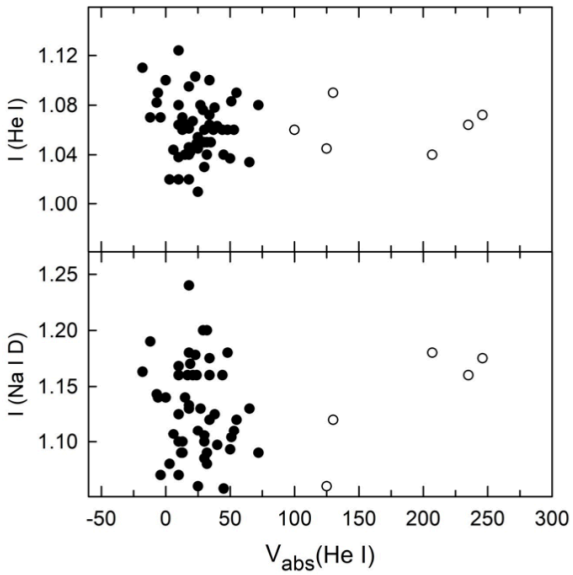


Figure 6b.

Figure 6

a. Variability of the emission equivalent width EW, its intensity I, and the radial velocity of the absorption components V_{abs} (the low-velocity component I is shown by filled circles, the high-velocity component II by open circles) for AB Aur.

b. Comparison of the radial velocities of the absorption components Vabs as a function of the emission intensity of helium I(He I) and the sodium resonance doublet I(Na I) (the low-velocity component I is shown by filled circles, the high-velocity component II by open circles) for AB Aur.

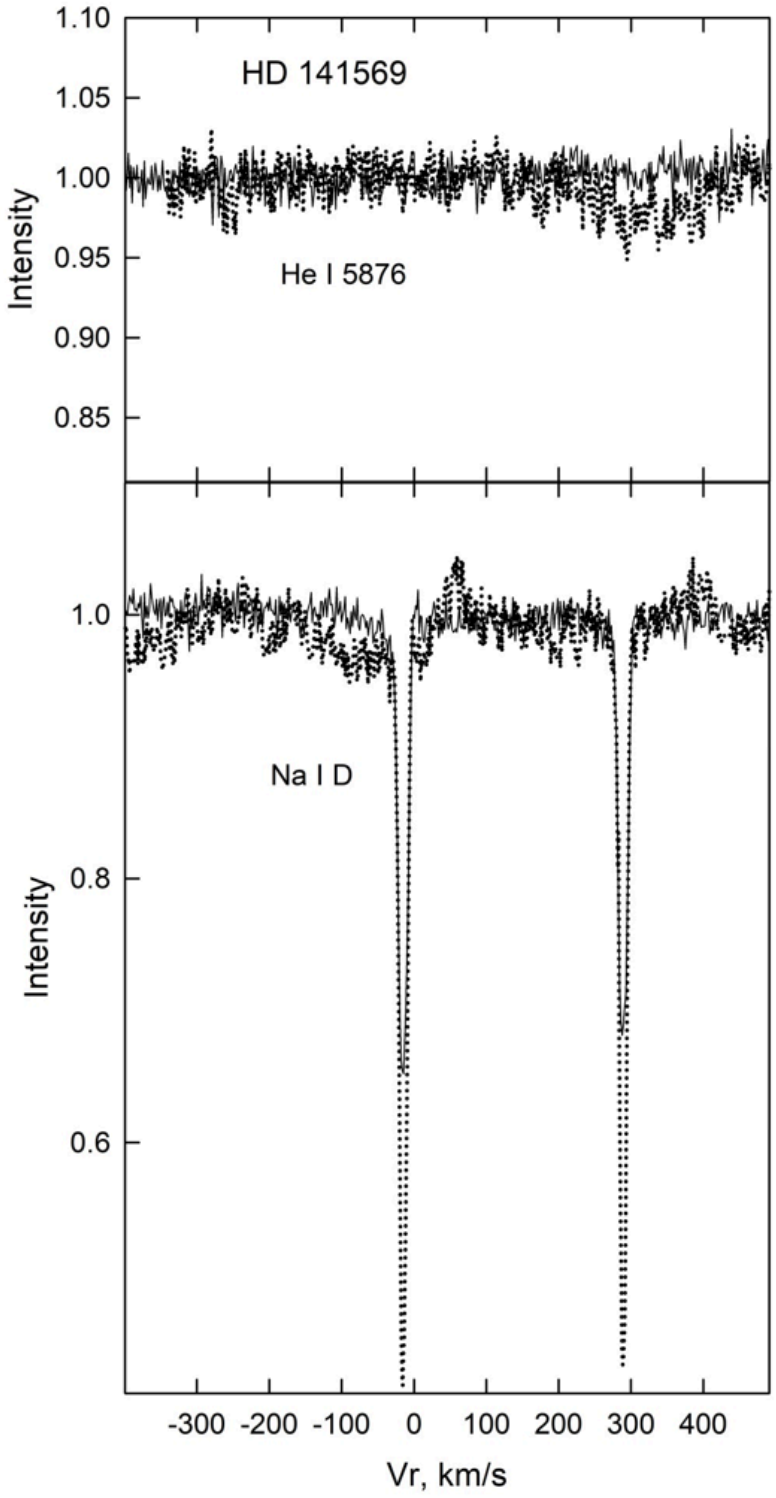


Figure 7

Example of two extreme types of profiles of the He I 5876 helium line (upper panel) and the Na I D sodium resonance doublet (lower panel) observed in HD 141569. Profiles obtained on 23 March 2010 are shown by the solid line; profiles obtained on 6 August 2020 are shown by dots.