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Doppler Tomography of the Circumstellar Disk of the Be Star κ Draconis

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Abstract: κ Draconis is a binary system with a classical Be star as the primary component. Its emission-line spectrum consists of hydrogen lines, notably the H_α line with a peak intensity ratio (V/R) variations phase-locked with the orbital period P = 61.55 days. Among binaries demonstrating the Be phenomenon, κ Dra stands out as one of a few systems with a discernible mass of its secondary component. Based on more than 200 spectra obtained in $2014-2023$, we verified the physical parameters and constructed the mass function. We used part of these data obtained in $2014-2021$ to investigate regions in the circumstellar disk of the primary component that emit the H_α line using the Doppler tomography method. The results show that the disk has a non-uniform density distribution with a prominent enhancement at $V_y \approx 99$ km s^{-1} and $V_x \approx -6$ km s^{-1} that corresponds to a cloud-like source of the double-peaked H_α line profile. We argue that this enhancement's motion is responsible for the periodic variations of the H_α V/R ratio, which is synchronised in orbital phase with the radial velocity (RV) of absorption lines from the atmosphere of the primary component.

Keywords: spectroscopy; doppler tomography; binary system; emission-line stars; circumstellar matter; variable stars

1. Introduction

Classical Be stars are B-type non-supergiants distinguished by their rapid rotation and emission lines in spectra, along with a notable infrared excess [1]. The pioneering model proposed by Struve [2] attributes these emission lines to recombination processes within a gaseous, geometrically thin, equatorial circumstellar disk. The hypothesis that Be stars could be members of binary systems that have undergone mass transfer emerged as an explanation for their rapid rotation [3]. This theory suggests that mass and angular momentum transfer from an originally more massive secondary component could cause primary component to spin up and eventually become a Be star. It is reasonable to expect that the remaining stripped core of the companion, classified as a subdwarf star, can continue to influence the spectral characteristics of Be stars through tidal effects. The latter may also cause truncation of the circumstellar disk around the Be star [4].

Studies of circumstellar disks of Be stars are as important as the exploration of the binarity, because the two subjects are connected through tidal interaction between the system's components. While it is well-established that the disks serve as sources of line emission, including the H_α line, critical gaps remain in our understanding of the intensity distribution, structural configuration, and essential dynamical characteristics. Many Be stars demonstrate periodic variations of the intensity ratio of the H_α emission peaks commonly referred to as V/R ratio, where "V" stands for the "violet" and "R" stands for the "red" peak.

One way to explain these variations is the rotation of a fixed non-axisymmetric density structure in the circumstellar disk that surrounds the Be star. Such a structure can take form of a one- [5] or two-armed density spiral [6,7] or a hot spot [8]. Disks in Be stars have another feature: in some systems they tend to disappear for several years and reappear again suddenly. The mechanisms governing this phenomenon remain uncertain. A leading theory involves oscillations of the one-armed spiral structure in a Keplerian disk proposed by Okazaki [5], but what causes these oscillations is still an open discussion. Other possible explanations for long-term V/R variations are presented by Telting [9].

The object of this study, κ Draconis (κ Dra, HD 109387, HR 4787, 5 Dra) is a classical Be star. It has a long history of observations that started as early as 1888, according to Jessup [10] who concluded that variations of intensity of emission lines (see Figure 1) are cyclic with a period of $\approx$ 23 years. This behavior was confirmed by Juza *et al.* [11] and, later Saad *et al.* [12] corrected the cycle length to $\approx$ 22 years.

In 1991 Juza *et al.* [13] first reported κ Dra as a binary system with a circular orbit and an orbital period of P = 61.55 days. Saad *et al.* [14] found that V/R variations of the H_α line are phase-locked with the orbital period. The result was recently confirmed by Miroshnichenko *et al.* [15]. The most accurate fundamental parameters of the system were provided by Klement *et al.* [16].

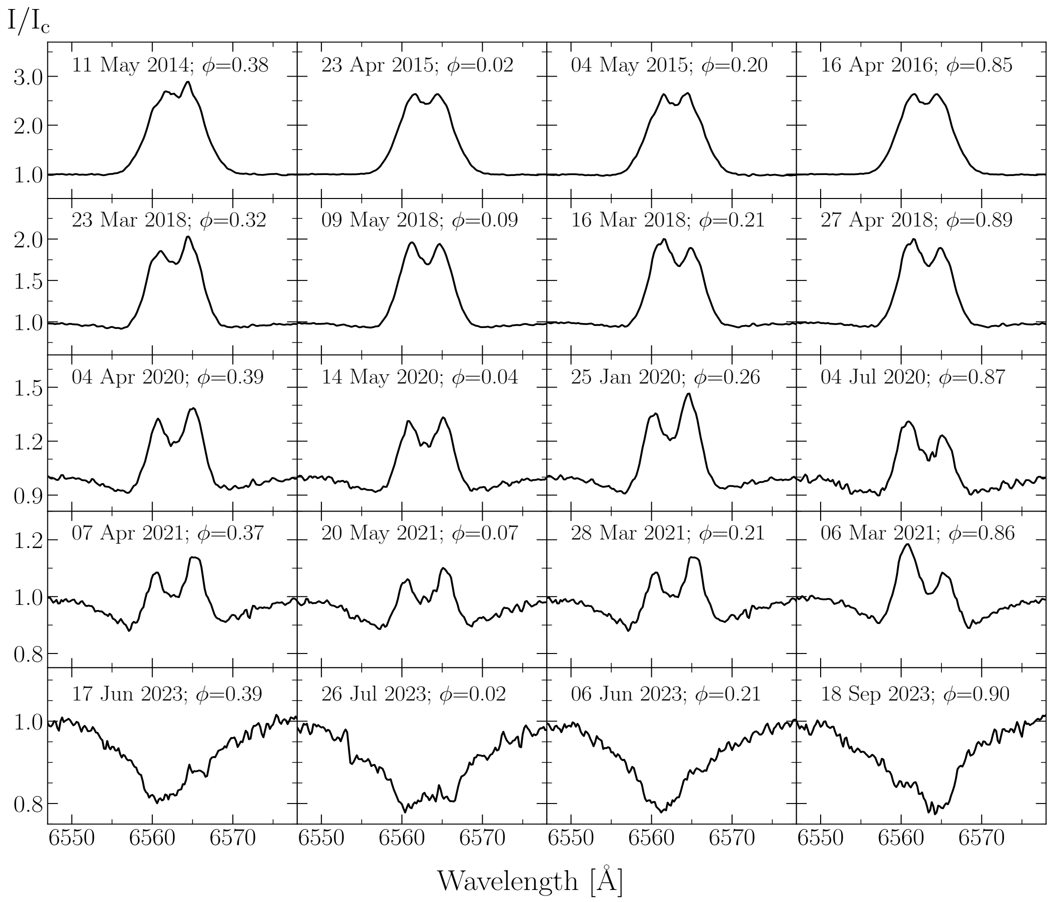

Figure 1. Examples of the H_α line profile in the spectra of κ Dra. The observational dates are shown in each panel. On the choice of the zero-phase epoch see Sect. 3.

In this paper we explore the circumstellar disk structure of the κ Dra binary system using the Doppler tomography method [17]. In Sect. 2 we describe our observations and the process of data reduction. In Sect. 3 we describe our analysis of the periodic V/R variations and radial velocities (RV) of the H_α line as well as of the RV variations of a set of absorption lines. The circumstellar disk study is presented in Sect. 3. The results are further discussed in Sect. 4. Finally, our conclusions are presented in Sect. 5.

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2. Observations and Data Reduction

The study is based on the spectroscopic data obtained using échelle spectrograph attached at the 0.81 ṁ telescope of the Three College Observatory (TCO) located in the central part of North Carolina, USA. Detailed information about TCO's equipment and observational program can be found in [18]. The spectra were taken between 2014 and 2023 with a spectral resolving power $R \sim 12,000$. The spectral range spans from $\sim 3740/4250$ Å to ~ 7890 Å without gaps between spectral orders. A typical time of an individual exposure was 180–300 seconds, and each spectrum consisted of several such exposures. Processing of the spectra was carried out using the *echelle* task in IRAF. The wavelength calibration was performed using a ThAr lamp.

A large fraction of our spectra in the H_α region are affected by telluric lines, particularly those acquired during late spring–early autumn seasons. To perform the V/R intensity ratio measurements, we originally divided our spectra by templates of telluric lines for different humidity levels created through interpolation of Gaussians corresponding to each telluric line. However, despite $\sim 70\%$ of the H_α line profiles contaminated in the peaks area, the results of the V/R measurements remained largely unaffected compared to the analysis of the same spectra before the cleaning procedure.

As a result, a total of 223 TCO spectra were analysed. Of these, only 101 spectra were employed for the H_α V/R and RV measurements as well as for the Doppler tomography due to the disappearance of the line emission in 2023. In addition, we employed 30 spectra from 2014−2016 taken from the BeSS (Be Star Spectra) database[1] with $R \sim 9,000 - 16,000$ to fill some gaps in our data. All the spectra were interpolated with an increment of $\Delta\lambda = 0.2$ Å.

3. H_α Line Evolution and Doppler Tomography

In Figure 1 we present selected H_α line profiles for different epochs and orbital phases. It is clearly visible that the line intensity decreases with time, while variations of the V/R ratio retain a strong sinusoidal character that is phase-locked with the orbital period. The changes in the H_α line flux over the period of our observations are illustrated by the evolution of its equivalent width (EW) in the bottom panel of Figure 2. However, The V/R ratio shows a stable behavior in relation to the orbital phase even when the emission component is barely above the continuum level (Figure 2, top panel). A similar graph of the H_α EW changes was published in Klement *et al.* [16] from a different dataset but with no analysis of the V/R variations.

From the RV curve of absorption lines in the spectral region 4370−4500 Å, we derived the orbital period P = 61.55(4) days and the semi-amplitude K_1 = 6.33(25) km s^{-1} for the primary component see [18] for details. The latter parameters give the mass function f(M_1) = 0.0016(2) $M_\odot$ close to those recently derived by Saad *et al.* [19] f(M_1) = 0.0021(1) $M_\odot$ and Klement *et al.* [16] f(M_1) = 0.0020(2) $M_\odot$. Thus in our analysis we used the components' masses M_1 = 3.65(48) $M_\odot$ and M_2 = 0.43(4) $M_\odot$ as well as the orbital inclination angle i = 50°.0(3°.4) from Klement *et al.* [16].

It is thought that the source of the H_α emission line in Be stars is a gaseous self-ejected (decretion) circumstellar disk. A trailed spectrum of a spectral region around the H_α line folded with the orbital period P = 61.55 days clearly shows a double-peaked structure of the line profile and the presence of an S-wave, which is typically associated with a hot spot in the disk (Figure 3, middle panels). By assuming a Keplerian velocity field, we can project our phase-resolved spectroscopy onto a predefined velocity framework to construct Doppler tomography of the system as proposed by Marsh and Horne [17]. Traditional objects of Doppler tomography are accretion disks in cataclysmic variables. Nevertheless, despite the fact that Be stars in binary systems usually have large separations between the components and likely already underwent the process of mass transfer, Doppler tomography is still proven helpful for studying circumstellar disks as a source of the H_α emission line [20].

[1] http://basebe.obspm.fr/basebe/

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Table 1. Adopted parameters for Doppler tomography of κ Dra.

Parameter	Value
P [days]	61.55 ± 0.04
T0 [HJD]	2459074.45 ± 0.43
γ [km s^{-1}]	-4.86 ± 0.18
K_1 [km s^{-1}]	6.33 ± 0.25
$f(M_1)$ [$M_\odot$]	0.0016 ± 0.0002

Parameters listed are as follows: P − orbital period, T0 — epoch of the inferior conjunction of the primary component, γ − systemic velocity, K_1 − semi-amplitude of the RV variations of the primary component, $f(M_1)$ − mass function. These parameters are derived by our team [15] and based on cross-correlation of the RV of absorption lines in the 4370−4500 Å region.

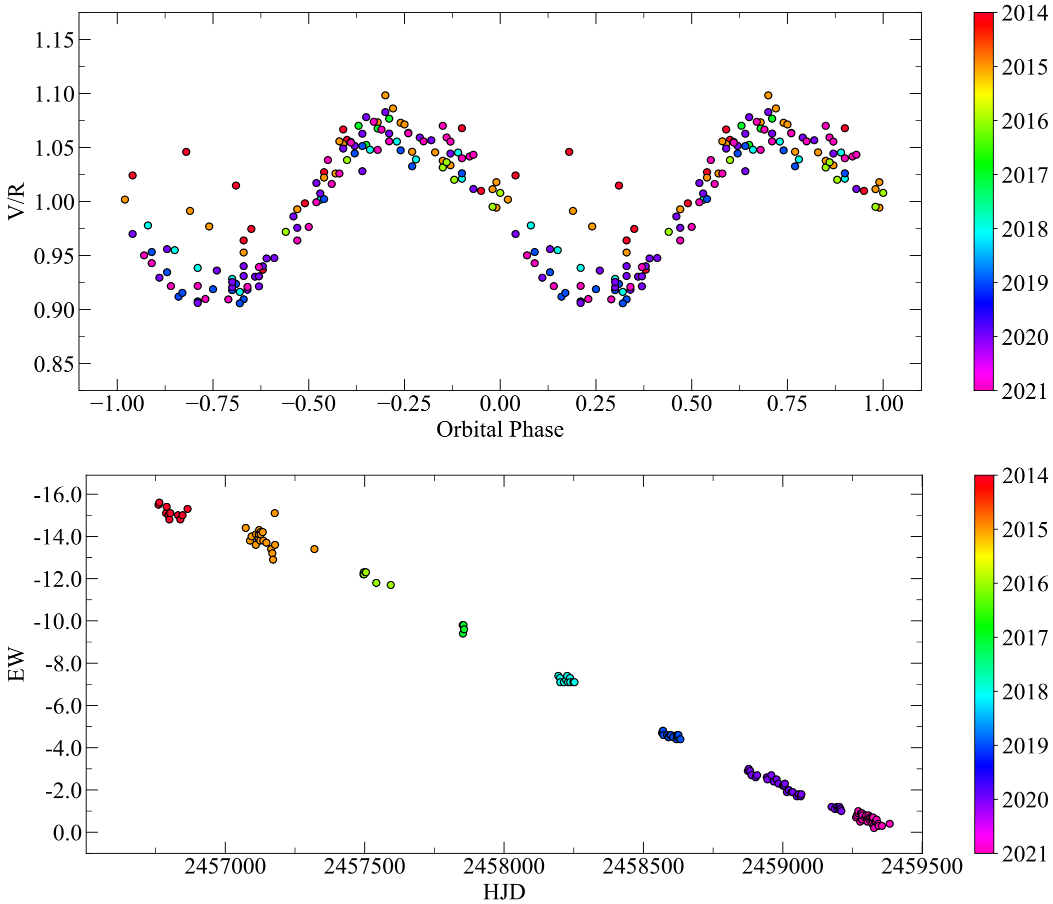

Figure 2. Top: V/R variations folded with the orbital period 61.55 days. **Bottom**: Temporal variations of the equivalent width (EW) of the Hα line. The colors correspond to observing dates as shown on the bar on the right.

Doppler tomography of κ Dra system was constructed based on the system parameters from Klement *et al.* [16] and parameters listed in Table 2. Our data provide a dense coverage of orbital phases and span over 40 orbital cycles. The procedure was executed via the *dopmap* program developed by Spruit [21]. In total, 131 spectra from several time intervals between 2014 and 2021 were used for this purpose. The emission line became too weak for the measurements after 2021.

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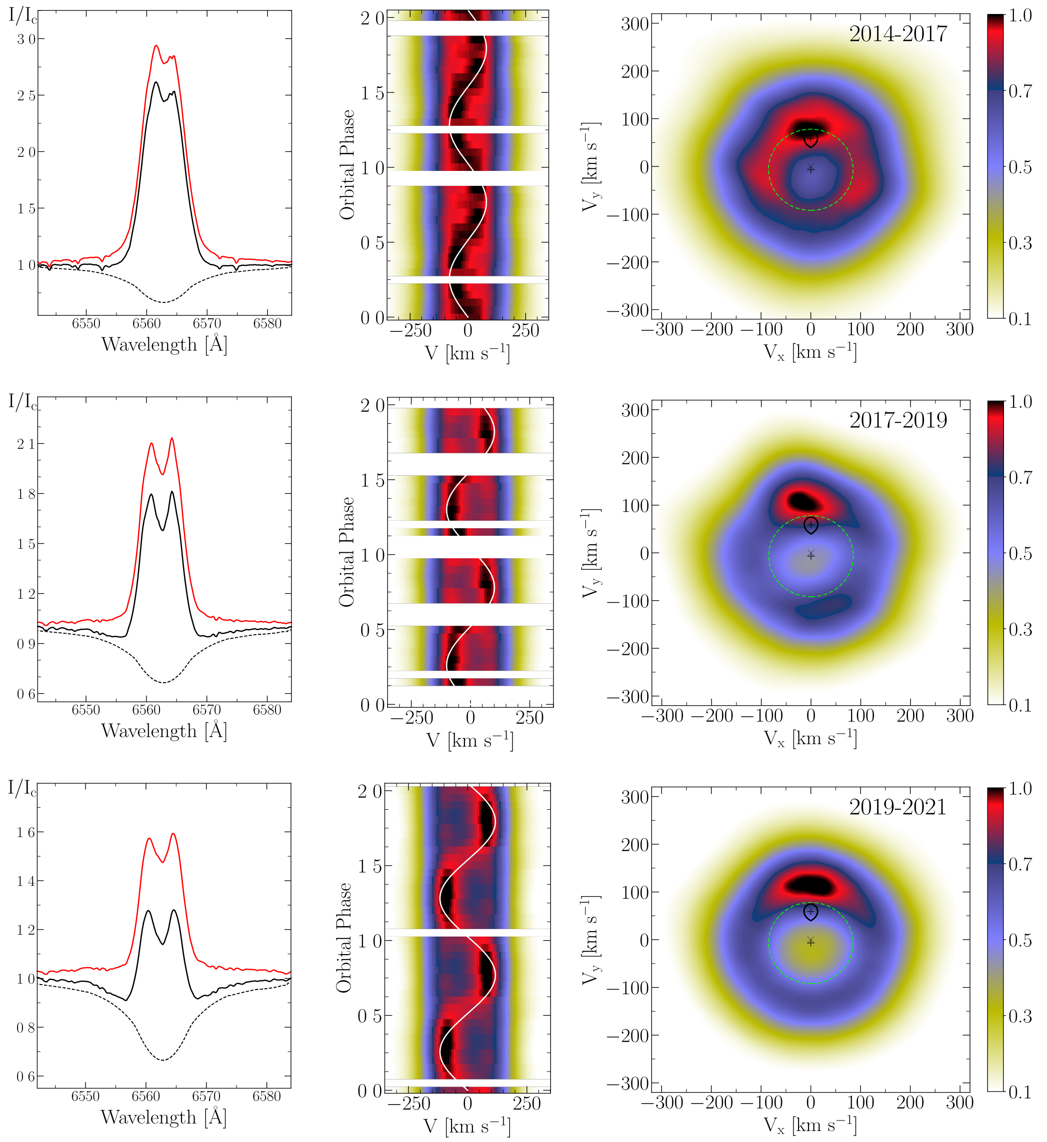

Figure 3. Left panels: Average Hα line profiles. Black solid line shows the original profile, dashed line is a model spectrum of the primary component's atmosphere, and solid red line is the result of subtraction of the model profile from the original one. Middle panels: Reconstructed trailed spectra of the Hα line folded with the orbital period P = 61.55 days. Right panels: Doppler maps of the system. The map is centered at the system's center of mass, which is marked by the cross. The plus sign marks the center of mass of the primary component at $V_y \approx -7$ km s^{-1} and $V_x = 0$ km s^{-1}. The center of mass of the secondary component is marked with another plus sign at $V_y \approx 50$ km s^{-1} and $V_x = 0$ km s^{-1} with the Roche lobe plotted around it. The dashed line marks $v \sin i = 85$ km s^{-1} that corresponds to the tidal truncation disk radius. The color of the Doppler maps corresponds to arbitrary units of emission intensity (the yellow-blue-red-black palette corresponds to a change from a low to high intensity).

Table 2. H_α line **source's** radial velocities and corresponding disk radii in different years.

Observation periods	V_x [km s^{-1}]	V_y [km s^{-1}]	$v \sin i$ [km s^{-1}]	v [km s^{-1}]	R_d [$R_\odot$]
2014-2017	-4 ± 52	80 ± 52	80 ± 74	104 ± 97	64
2017-2019	-13 ± 35	100 ± 28	101 ± 45	132 ± 59	40
2019-2021	1 ± 36	117 ± 28	117 ± 46	153 ± 60	30

Parameters listed are as follows: V_x and V_y − components of the RV in the plane of the disk, $v \sin i$ − RV of the mass center of the emitting region, calculated as $v \sin i = (V_x^2 + V_y^2)^{1/2}$, v − RV corrected for the orbital plane's inclination, R_d − radius of the disk, calculated as radius of a Keplerian orbit for a given RV.

We divided our spectral data into three slightly overlapping blocks to explore the disk structure evolution. The first block (2014−2017) corresponds to $EW_{H_\alpha} \lesssim -9$ Å, the second one (2017−2019) covers a range of EW_{H_α} from ≈ -10 Å to ≈ -4 Å and the last one (2019−2021) when $EW_{H_\alpha} \gtrsim -5$ Å. To exclude the absorption part of the line, we subtracted a model spectrum of the H_α line from all spectra (see Figure 3, left panels). The model spectrum of the stellar atmosphere was constructed via the SPECTRUM program [22] using Kurucz/Castelli data [23] corresponding to a star with the following parameters: $T_{\rm eff}$ = 14000 K, log g = 3.5 and $v \sin i$ = 200 km s^{-1} that are close to those provided by Klement *et al.* [16].

In the left panel of Figure 3, we show the average resulting line profiles (red lines). In the right panels of Figure 3, we present Doppler maps obtained from 44 spectra taken in 2014−2017 (top), 31 spectra taken in 2017−2019 (middle), and 76 spectra taken in 2019−2021 (bottom). As seen from the trailed spectra, orbital phases are well covered. All the Doppler maps show the presence of a torus-like structure, and an extended bright spot at $V_y \sim 100$ km s^{-1} and $V_x \approx 0$ km s^{-1}. The map for 2014−2017 shows a non-uniform ring of the disk emission (V≈100 km s^{-1}) with a prominent intensity enhancement centered at $V_y \approx 80$ km s^{-1} and $V_x \approx$ -4 km s^{-1}. The emission concentrated near the disk's tidal truncation radius at $R_t = 56\ R_\odot$ [24] (dashed line in the Doppler maps):

$$\frac{R_t}{a} = \frac{0.6}{1+q} \tag{1}$$

where a is the distance between the system components and $q = M_2/M_1$ is their mass ratio.

In the 2017−2019 map, the maximum intensity from the spot moved to $V_y \approx 100$ km s^{-1} and $V_x \approx$ -13 km s^{-1}, and another, less intense compact emission appeared on the opposite side of the disk at $V_y \approx$ -100 km s^{-1} and $V_x \approx 32$ km s^{-1}. The Doppler map for the last time interval (2019−2021), when the disk emission was the weakest, has a similar structure with a small clockwise displacement of the spots. The brighter spot also looks more intense in comparison with the virtually invisible opposite one.

We measured positions of the maximum intensity of the bright spot by fitting it to a single Gaussian in the X and Y direction on the Doppler maps. The measurement results are given in Table 2 and shown by a white line over the trailed spectra in Figure 3. The errors correspond to 1σ of the Gaussian fit and reflect the velocity dispersion within the spot. Assuming Keplerian velocities in the disk and that the spot is located in the disk's outer part, we estimate its radius R_d using the following equation:

$$R_d = \frac{GM_1}{v^2} \tag{2}$$

where v is the maximum velocity within the bright spot, G is the gravitational constant, and M is the mass of the star. The outer disk radii for the different epochs are given in the last column of Table 2. As one can see in Figure 4, the disk radius decreases along with decreasing the H_α EW.

Assuming Keplerian velocities of particles in the disk, we transformed the Doppler (velocity) map into the XY plane of the system (Figure 4). The color map in the XY plane clearly shows a strong extended emission from the disk's outer region located on the line that connects the centers of the system components. The less massive companion can not fill its Roche lobe, therefore the excess of emission here is probably due to tidal disturbances of the disk by the companion which provide a high velocity dispersion and deviations from Keplerian motion. The bright region on the opposite side of the secondary component is probably caused by a non-Keplerian motion in the disk which is expected here. We believe that the bright spot is the source of the Hα line V/R variations.

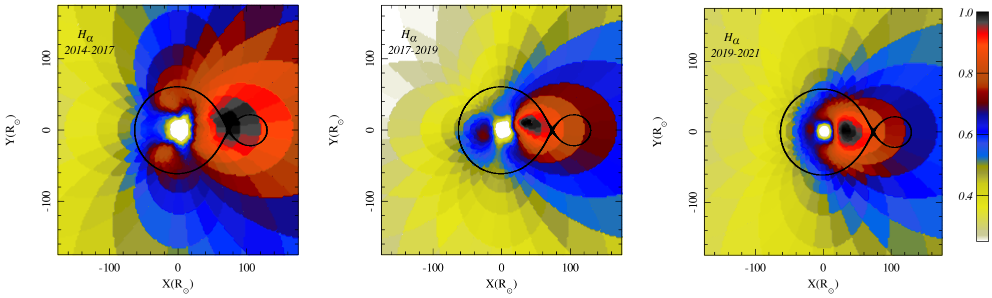

Figure 4. The brightness distribution in the disk transformed from the Doppler map of the Hα emission line to the XY plane of the system. The colorbar shows normalized relative intensity. The Be star is located at the origin.

4. Discussion

Currently κ Dra remains the only confirmed Be+sdB binary amidst growing number of Be+sdO systems e.g., [25] . In this research we explored how the emitting region structure in the circumstellar disk κ Dra was changing throughout the disk disappearance process. The latter tendency does not seem to be dependant on the secondary component's parameters. For instance, such a phenomenon was observed in π Aqr [20], where the secondary companion is either a main sequence star [26] or a white dwarf [27].

Despite the gradual decrease of the Hα line intensity, its V/R variations of the line profile remained phase-locked with the orbital period until the time, when measurements could not be taken with a sufficient accuracy. It implies that, as the density of the disk decreases, the distribution of the emitting matter in it remains stable. The Doppler maps constructed for different epochs of the κ Dra disk evolution show an emitting region produced by a density enhancement centered in the outer parts of the disk that faces the secondary companion. There is a number of Be + sdO binaries where the V/R variations are also locked with the orbital period see [15] for a recent discussion and may be caused by a similar mechanism.

Porter and Rivinius [28] described several models that were proposed to explain the circumstellar disk properties in Be stars. Theoretical explanations for the phase-locked V/R variations concentrated around one-armed density waves in a near-Keplerian disk [5], which can generally reproduce the line profiles [29]. Panoglou *et al.* [6] proposed that the phase-locked variations can be associated with a two-armed spiral structure in the disk, while longer-term V/R variations were considered to be caused by a one-armed spiral [30]. Tidal disturbances and the disk heating from the side of the secondary companion are also possible contributors to the observed effects.

Based on the Doppler maps of κ Dra (see Figure 3), we suggest that the V/R variations are caused by a large hot spot located near the outer radius of the disk closest to the secondary companion. The spot position is stable as the disk radius decreases. The disk itself looks ragged, and its structure and location of the regions with various brightness slightly vary during the disk evolution (see Figure 4). We suggest that the origin of this spot is mainly caused by irradiation and tidal effects induced on the disk by the secondary companion.

5. Conclusions

We explored the evolution of the region responsible for the Hα line emission in the κ Dra binary system throughout the disappearance process of the circumstellar disk around the primary component. The following results were obtained:

1. Despite the gradual decrease of the Hα line intensity, its V/R variations remained phase-locked with the orbital period.
2. The Doppler maps constructed throughout the disk evolution show the presence of a nearly stable bright emitting region located in the outer part of the disk in the direction of the secondary companion. We suggest that this structure is responsible for the V/R variations observed in the Hα line profile.
3. The origin of the hot spot is most likely related to the forming one-armed spiral structure in the disk, tidal effects, and irradiation from the secondary companion.

Alternative modelling of the disk structure at various levels of the emission-line strengths would be important to verify this hypothesis.

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Data Availability Statement: Original spectra reported in this study are available on request to the A.M. via email at a_mirosh@uncg.edu.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript: RV – radial velocity, V/R – violet-to-red peak intensity ratio in a double-peaked emission-line profile, R – spectral resolving power, EW – equivalent width, TCO – Three College Observatory.

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