ABSTRACT

of the dissertation work (series of articles) for the Doctor of Philosophy (PhD) degree
in the educational program «8D05307 – Physics and Astronomy»

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Structure and evolution of circumstellar matter in Be stars

General characteristics of the work

This dissertation work (series of articles) investigates the structure and evolution of circumstellar disks in classical Be stars using Doppler tomography. The focus is on two binary systems: κ Draconis and HD 698, that show clear signs of disk asymmetries potentially driven by their companion stars. κ Dra is a well-known Be binary with a documented phase-locked V/R variability. HD 698 was previously suspected of hosting a black hole, and only recently was confirmed to contain a stripped bloated companion. These systems are unique objects for studying how companions affect Be-star disks.

Relevance of the topic

Classical Be stars are rapidly rotating B-type stars surrounded by Keplerian gaseous disks. These disks produce double-peaked Balmer emission lines and show violet-to-red (V/R) variations. In isolated Be stars, long-term V/R cycles are often explained by a precessing one-armed density wave (Okazaki, 1997). However, many Be stars are in binaries, and some show V/R variations phase-locked to the orbital period. Examples include 4 Hercules (Koubský et al., 1997), π Aquarii (Bjorkman et al., 2002), and κ Draconis (Saad et al., 2005). These cases could not be described by the Okazaki's precession model and suggest direct gravitational influence from the companion.

If V/R variability follows the orbit, the asymmetry likely results from tidal or radiative effects, not intrinsic disk oscillations. Traditional spectroscopy can track these variations and offer constraints on disk kinematics but cannot isolate the underlying emission geometry. Hydrodynamic models can simulate this but are computationally demanding and degenerate. Doppler tomography offers a direct, data-driven alternative.

Doppler tomography, developed by Marsh and Horne (1988), reconstructs a 2D map of emission in velocity space using phase-resolved spectra. It maps line-emitting regions in the rotating binary frame. The method reconstructs the full spectral time series as emission distribution in velocity space and does not rely on complex physical simulations. Given known orbital parameters, tomography is efficient and straightforward.

The first application to a classical Be star was π Aquarii (Zharikov et al., 2013), a binary with an 84-day orbit. From over 40 orbital cycles of Hα spectra, they built a tomogram showing an asymmetric emission ring with a bright spot. The V/R variation matched the orbital period (~84.2 days), proving the asymmetry

was orbitally locked. This confirmed that the density enhancement co-rotated with the companion, not precessing freely.

Following this, our group extended the method to other Be binaries. In κ Draconis (P = 61.55 days), our tomography revealed a concentrated emission feature, corresponding to the density enhancement that drives the V/R oscillation. The decade-long monitoring demonstrated that this V/R modulation remained phase-locked to the orbital period even as the disk dissipated and nearly vanished. Our analysis (Gabitova et al., 2024) also tracked disk evolution during a dissipation event, showing how tomography can monitor disk structure changes over time.

HD 698 (V742 Cassiopeia), a 56-day Be binary, was once suspected to host a black hole. Interferometric measurements (Rivinius et al., 2025) revealed that there is likely a stripped bloated companion. Tomography in this dissertation work was applied to investigate possible disk perturbations from the companion. The results show a unique extra emission source moving at velocities associated with the companion and, after its removal, persistent asymmetric structure in the Hα-emitting disk, possibly a two-armed pattern locked to the orbit.

Doppler tomography enables model-independent detection and characterization of disk asymmetries in Be star binaries. Unlike theoretical simulations, it reconstructs emission structures directly from spectral data, without relying on assumptions about density distributions or specific perturbation modes, aside from assuming Keplerian, circular motion. The resulting velocity-space maps inherently match the observed spectra and require minimal computation.

This method is efficient: once phase-resolved spectra are available, the reconstruction runs on a standard computer. It does not need interferometry, X-rays, or simulations. Any Be binary with known orbital parameters and a time series of spectra can be analyzed.

Tomography can effectively locate emission regions and identify orbit-locked structures. In π Aquarii (Zharikov et al., 2013), the tomogram confirmed the companion's role in shaping the disk. In κ Draconis and HD 698, our maps show clear signatures of companion-induced perturbations.

These findings support the idea that companion interaction can play a significant role in shaping disk structure in Be binaries. The disks retain imprints of both past and ongoing interaction effects. Tomography bridges theory and observation, showing how disk structures evolve and respond to binary dynamics.

In summary, Doppler tomography is a useful instrument for mapping circumstellar disks in Be binaries. It complements other methods and enables statistical comparisons across systems. As more binaries are studied, the understanding of disk behavior improves, especially in the context of binary evolution in Be stars.

The goal of the study is to determine the companion–disk interaction in Be binary stars by testing V/R phase-locking, refining orbital/geometric parameters, and imaging velocity-space structure.

Research objectives

1. Measure V/R ratio in suitable spectral lines, establish its relation to the orbital motion.

2. Determine fundamental parameters of the systems under study by fitting radial velocity curves and line profiles.

3. Construct and interpret Doppler tomograms to identify and characterize companion-driven disk structures.

Objects of the study: Be stars κ Draconis and HD 698.

Methods

1. Processing échelle spectra via bias/flat correction, wavelength calibration, heliocentric correction, order merging, continuum normalization, and telluric removal using IRAF package and Python scripts (public access and own codes).

2. Measuring absorption-line RVs by cross-correlating selected regions with templates, estimating uncertainties from the correlation peak width via Tonry–Davis R statistic.

3. Measuring emission-line RVs using the double-Gaussian wings method, or the bisector method.

4. Searching for periodicities in RV and V/R series using Lomb–Scargle and phase-dispersion methods, and phase folding.

5. Fitting RV curves to derive orbital parameters.

6. Modeling and subtracting the lines' components as a Doppler-shifted Gaussian to isolate the main line profile.

7. Reconstructing Doppler tomograms with maximum-entropy regularization (dopmap program).

Provisions for the defense

1. In the object κ Draconis, the phase synchronization of the Hα line peak ratio (V/R) with the orbital period is caused by the companion star's influence on the circumstellar disk throughout the entire disk dissipation period, from maximum intensity to complete disappearance.

2. According to Doppler tomography results, this phase-synchronized peak ratio originates in a bright emitting region in the outer disk, always facing the companion star. This region exists due to the tidal or radiative influence of the companion star and does not disappear even at the late stages of disk dissipation, as the disk radius contracts from ~64 $R_\odot$ to ~30 $R_\odot$.

3. In the object HD 698, the central emission peak in the Hα line profile is not associated with the circumstellar disk but with an additional source of radiation moving at velocities close to those of the companion star, which has a dynamical mass of 1.1±0.2 $M_\odot$.

Scientific novelty of the studies can be summarized by the following points:

1. For the first time, a full Be-star disk dissipation event was explored via Doppler tomography of κ Draconis system.

2. First identification and kinematic characterization of a narrow Hα emission component co-moving with the companion in HD 698.

3. First direct, self-consistent constraints on the companion's mass in HD 698 (RV, tomography) that reject the black-hole scenario previously suggested for this

system and instead support a stripped bloated companion within quantified uncertainties.

Theoretical and practical significance

The results establish companions in Be binaries as the driver of non-axisymmetric structure in Be-star disks by tying V/R variability to orbital phase and mapping a companion-facing spot with Doppler tomography, thereby constraining disk truncation, warping, and stream-impact scenarios within the Keplerian framework. Practically, the work delivers a reproducible end-to-end methodology—standardized line measurements, period analysis, phase-resolved tomography, and optionally, targeted component subtraction for companion-linked emission, with documented settings that make the approach portable to other Be binaries.

Author's contribution

Results of the study were obtained personally by the candidate. The setting of goals and objectives and the conduct of the study were supervised by scientific advisors. Contribution to the publications is as stated in the «Author Contributions» section at the end of each publication.

Validity of the results

The reliability of the results is ensured by multi-epoch, multi-instrument spectroscopy with calibrated wavelength zero-points; by reproducibility of RV and V/R measurements; by detection of the same orbital period in both RV and V/R series; by coherent orbital solutions that are in agreement with previous studies; by geometric and kinematic consistency of mapped structures with binary dynamics; by explicit tests against parameter's range and alternative scenarios; and by full documentation of ephemerides, measurement windows, and reconstruction settings enabling exact reproduction of the figures.

Publications

The main results of the research work have been published in 3 papers, including:

Articles in high-impact journals indexed in the Web of Science Core Collection or Scopus:

1. **Gabitova I. A.**, Zharikov S. V., Miroshnichenko A. S., Carciofi A., Khokhlov A. A., Agishev A., and Prendergast P. Doppler Tomography of the Be Star HD 698 //Galaxies. – 2025. – Vol. 13. – № 4. DOI: 10.3390/galaxies13040080. (**Journal Impact Factor – 3.8, WoS – Q2, Scopus – 74**)

2. **Gabitova I. A.**, Miroshnichenko A. S., Zharikov S. V., Amantayeva A., and Khokhlov S. A. Doppler Tomography of the Circumstellar Disk of the Be Star κ Draconis //Galaxies. – 2024. – Vol.12. – №3. DOI: 10.3390/galaxies12030023. (**Journal Impact Factor – 3.8, WoS – Q2, Scopus – 74**)

3. Miroshnichenko A. S., Chari R., Danford S., Prendergast P., Aarnio A. N., Andronov I. L., Chinarova L. L., Lytle A., Amantayeva A., **Gabitova I. A.**, Vaidman N. L., Baktybayev S. S., and Khokhlov S. A. Searching for Phase-Locked Variations of the Emission-Line Profiles in Binary Be Stars //Galaxies. – 2023. –

Vol.11. – №4. DOI: 10.3390/galaxies11040083. (**Journal Impact Factor – 3.2, WoS – Q2, Scopus – 66**)

Dissemination of the results

The results obtained in this work were reported and discussed:

- at the International Scientific Conference "Hot Stars: Life with Circumstellar Matter" (2024, Almaty, Kazakhstan);

- at the 23rd Gamow International Conference on Astronomy "Astronomy and beyond: Astrophysics, Cosmology and Gravitation, Astroparticle Physics, Radioastronomy, Astrobiology and Genetics" (2023, Odessa, Ukraine).

Alignment of the work with institutional research plans

This work was carried out in accordance with the plans of fundamental research works of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan «Grant financing of scientific research» on the topic: «AP23484898 – Development of a modern technique for determining the fundamental parameters of Galactic hot supergiants».