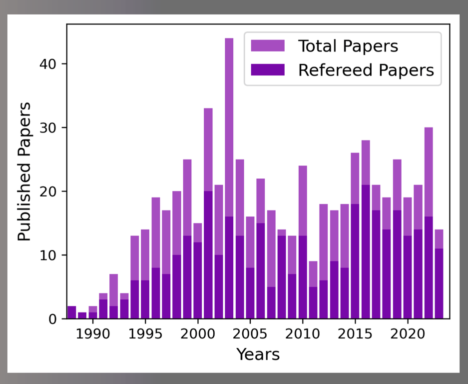
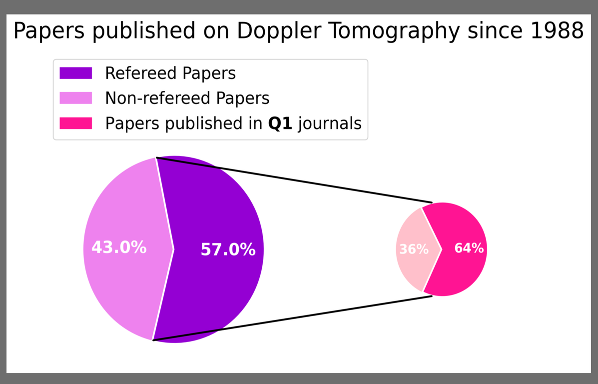
DOPPLER TOMOGRAPHY

What is Doppler tomography?

Doppler tomography is a technique used in astrophysics to understand complex emission line profile variations by building the velocity distribution of its source in a two-dimensional plane. It is commonly applied to binary star systems, specifically, the accretion disks surrounding compact celestial objects such as white dwarfs, neutron stars, or black holes.





Papers on Doppler tomography are regularly published in high-impact journals, such as MNRAS, AAS, A&A, ApJ and AJ.

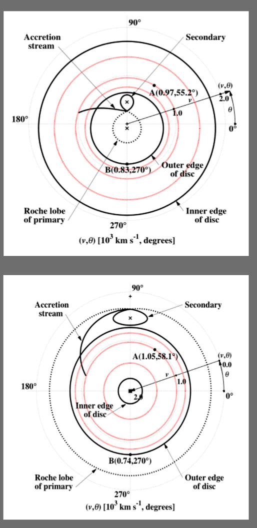
How does it work?

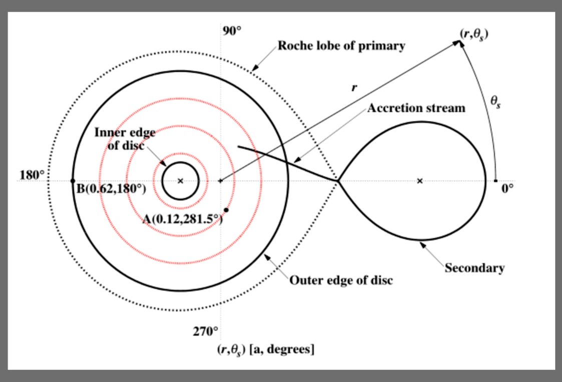
Doppler tomography, developed by Marsh T. R. and Horne K. in 1988, aims to create a model-independent velocity map that resolves the distribution of line emission/absorption in a binary system using a series of spectra. It operates under the assumption that orbiting material follows a sinusoidal radial velocity curve:

$$v_R(\varphi) = \gamma - v_x*\cos(2\pi\varphi) + v_y*\sin(2\pi\varphi).$$

Marsh T. R., Horne K., 1988, MNRAS, 235, 269

Here, φ is the orbital phase, γ is the systemic velocity of the system, and v_x and v_y are the radial velocity semi-amplitudes. Then we can use the observed spectra as a function of orbital phase to calculate the strength of the line emission/absorption as a function of velocity. This, in turn, can be used to construct a velocity 'image' or map of the orbiting material in velocity space, defined as the strength of the line emission/absorption as a function of velocity, $I(v_x, v_y)$.



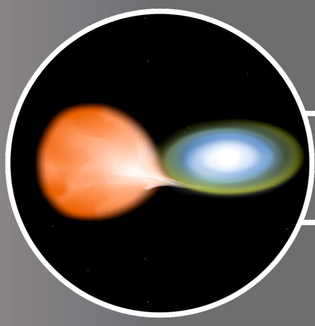


Right plot: geometry of a binary system with accretion.
Upper left plot: the same system geometry in the velocity space.
Lower left plot: the same system geometry in the alternative, inside-out velocity space.

Kotze, Enrico & Potter, S. & McBride, V.A.. 2015, A&A, 579.

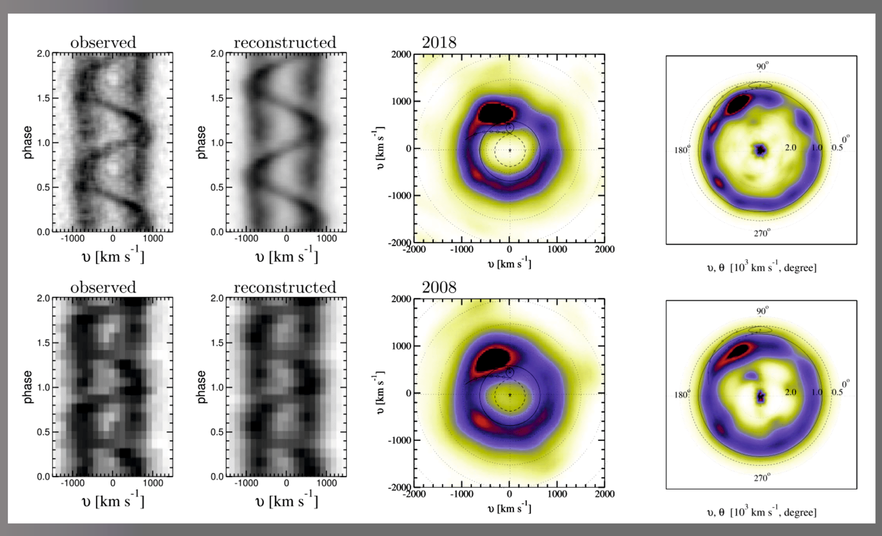
What objects do we explore?

Doppler tomography has been used to study a wide range of astrophysical objects, including cataclysmic variable stars, X-ray binary systems, novae and more. It is particularly valuable for understanding how matter is transferred between stars in binary systems. In other words, we use Doppler tomography to study astrophysical objects where the motion of matter is a critical factor in understanding their behavior.

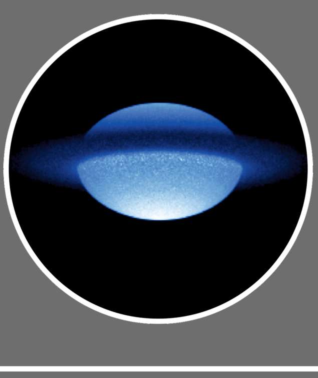


Cataclysmic variables

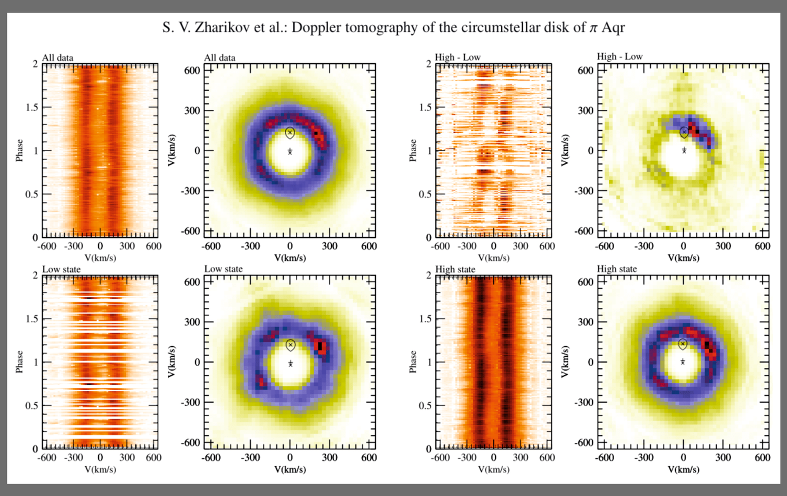
Cataclysmic variables (CVs) play a crucial role in our understanding of stellar evolution. These binary star systems, consisting of a white dwarf and a companion star, are known for their sporadic and explosive outbursts resulting from active processes of mass transfer. In fact, Doppler tomography was originally invented to study accretion disks in CVs. By mapping the velocity distribution within these disks, Doppler tomography provides insights into the complex processes of mass transfer, accretion, and energy release.



Amantayeva, A., Zharikov, S., Page, K., et al. 2021, The Astrophysical Journal, 918, 58

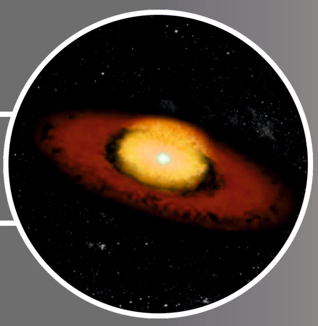


Be stars



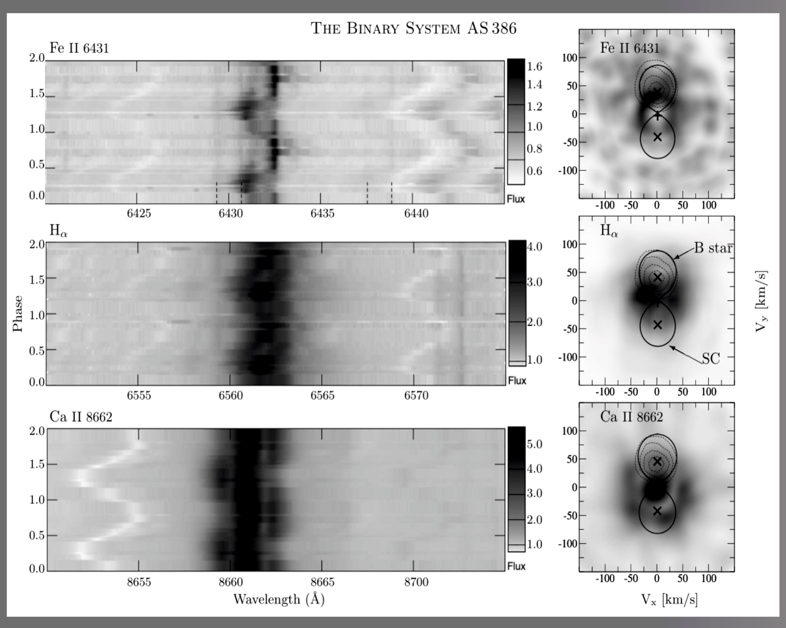
Be stars, a class of B-type stars, are known for their rapid rotation, presence of IR excess and emission lines in optical spectra, which originate from gaseous circumstellar (not accretion!) disks. Doppler tomography can be used to map the velocity distribution within these disks. It allows us to explore interactions between the star and its surrounding material, shedding light on the mechanisms behind Be stars unique spectral features and evolution status.

Zharikov, S. V., Miroshnichenko, A. S., Pollmann, E., et al. 2013, A&A, 560, A30, doi: 10.1051/0004-6361/201322114



B[e] stars

B[e] stars is another unique stellar class. Unlike Be stars, the disks in B[e] stars are notably larger, containing both dust and gas. This combination produces a more substantial infrared excess in their spectra. Additionally, the emission lines observed in B[e] stars can include forbidden lines, hence the name. Doppler tomography provides valuable insights into the dynamic behavior of these systems, helping us understand the origin of spectral features of B[e] stars.



Khokhlov, S. A., Miroshnichenko, A. S., Zharikov, S. V., et al. 2018, ApJ, 856, 158

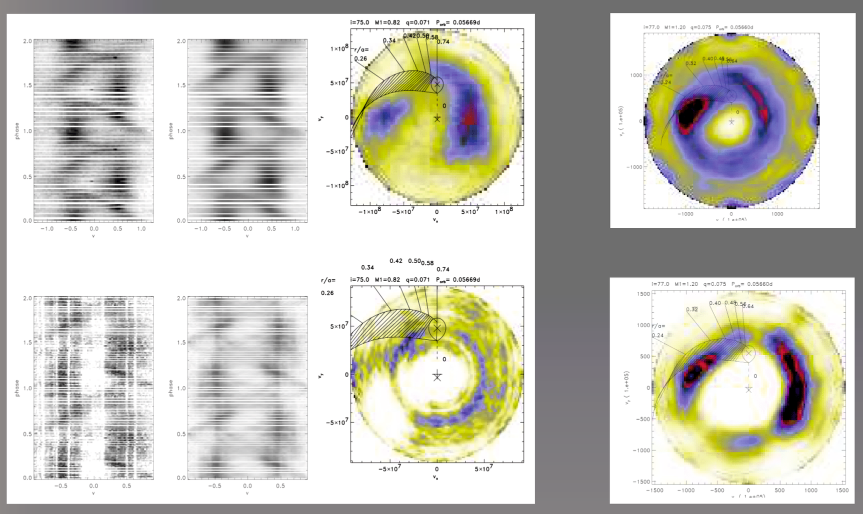
How to compute Doppler tomography?

There are a number of numerical codes that implement Marsh and Horne's ideas with a few key differences. Look below at the examples of using some of those codes to explore one of the most prominent cataclysmic variable stars – WZ Sge.

Dopmap

Dopmap uses fast maximum entropy method to optimize the Doppler map fitting to observed data. Infromation entropy of the image is used as a parameter for the optimization which allows to achieve the best match between the reconstructed spectrum and the input data. The optimization is done iteratively to reach a unique maximum.

Look below for the Doppler tomography constructed with dopmap using HeII line (right image by Baba et al. and upper left image by Echevarrıa) and Hβ line (lower left image by Echevarrıa) taken during WZ Sge outburst in 2001.

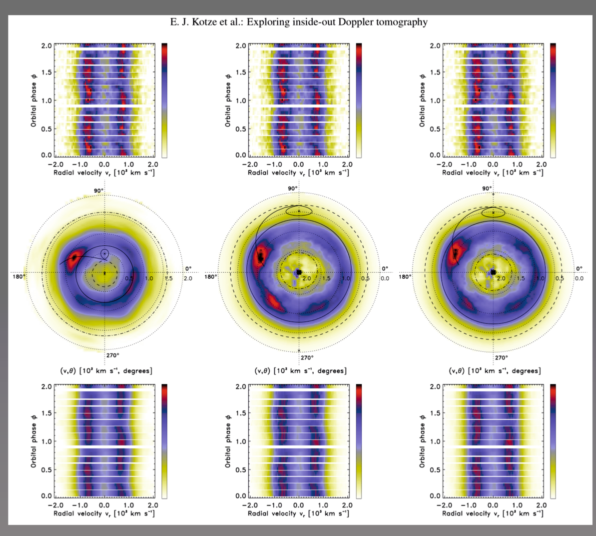


Baba, H., Sadakane, K., Norimoto, Y., et al. 2002, PASJ, 54, L7
Echevarria, J.. 2012, Memorie della Societa Astronomica Italiana.

Doptomog

Doptomog code, introduced by Kotze, Potter & McBride in 2015, allows to construct inside-out tomogram independently of the standard tomogram by directly projecting phase-resolved spectra onto an inside-out velocity coordinate frame. For the inside-out framework, the zero-velocity origin is transposed to the outer circumference and the maximum velocities to the origin of the velocity space.

That way, center of the image is uninterpretable, but inner parts of the disk are more detailed. Look below for the comparison of standard Doppler tomogram for WZ Sge in quiescence and an inside-out one. Both are using Hα line.

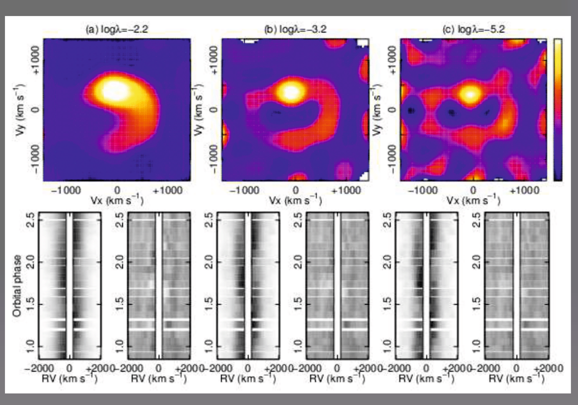


Kotze, Enrico & Potter, S. & McBride, V.A.. 2015, A&A, 579. 10.1051/0004-6361/201526381.

DTTVM

«Doppler Tomography using Total Variation Minimization" (DTTVM) was developed in 2013 by Uemura, M., Kato, T., Nogami, D., and Mennickent, R.. This method is designed for reconstructing Doppler maps, with emphasis on its ability to handle localized and non-axisymmetric profiles with sharp edges, especially when the input data is limited in quantity.

One notable advantage of DTTVM is its reduced dependence on hyperparameters and the presence of absorption cores when compared to models based on the maximum entropy method. Look below for the Doppler tomography of WZ Sge during outburst in 2001 constructed using DTTVM.



Uemura, M., Kato, T., Nogami, D., & Mennickent, R. 2015, PASJ, 67, 22