Yet another spectro-interferometric study of the gas distribution in the enigmatic semi-detached binary $\beta$ Lyrae

J. Nemravová$^1$, P. Harmanec$^1$, D. Mourard$^2$, A. Meilland$^2$

$^1$Astronomický ústav Univerzity Karlovy, Matematicko-fyzikální fakulta, Univerzita Karlova v Praze,
$^2$Laboratoire Lagrange, UMR 7293 UNS-CNRS-OCA, Boulevard de l’Observatoire, BP 4229, 06304, Nice Cedex 4, France.

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M A S S T R A N S F E R I N B I N A R I E S

- Inevitable fate of the majority of close binaries.
  - Huge impact on the evolution of both components.
  - The initial step towards various "exotic" stars such as helium stars, Be stars, mergers and many more.
- Two phases:
  - Rapid one, possibly non-conservative, 
    \[ \frac{dM}{dt} \approx 10^{-5} - 10^{-6} \, M_\odot \cdot \text{yr}^{-1}, \]
    \[ \Delta T \approx 0.01 - 0.1 \, \text{Myr.} \]
  - Slow one, conservative,
    \[ \frac{dM}{dt} \approx 10^{-7} - 10^{-9} \, M_\odot \cdot \text{yr}^{-1}, \]
    \[ \Delta T \approx 1 - 10 \, \text{Myr.} \]
  - The bulk of the mass is exchanged during the short rapid phase. Systems in this phase are very rare.
β LYRAE, ENCHANTÉ I

- Bright ($V = 3.42$ mag) Be star [Secchi 1867].
- Semi-detached *eclipsing* binary, the orbital period $P = 12.94$ d, that is steadily growing by $19 \text{ s yr}^{-1}$ [Ak et al., 2007].
- *Most likely undergoing the rapid mass transfer phase.*
Beta Lyrae

Gainer
B0.5V
30000K
13.05Msol

Dönor
B6-8II
13000K
2.91 Msol

Accretion disk
A5III
9000K (rim)

0.2 mas

NOT ON A GREEN MEADOW

- The object has been vastly studied >1300 studies mention it:
  - Focusing on the interferometric studies:
    - [Mourard et al., 1992] - GI2T interferometer, the first study of visibility variations in spectral lines of $\beta$ Lyrae in visible.
    - [Harmanec et al., 1996] - spectro-photo-interferometric study, jet-like structures detected.
    - [Zhao et al., 2008] - H band interferometry with MIRC@CHARA interferometry, imaging of the accretion disk and the donor.
    - [Schmitt et al., 2009] imaging of the H$\alpha$-forming regions at low resolution, jets were not detected.
    - [Bonneau and Chesneau et al., 2011] spectro-interferometry with VEGA@CHARA in visible, line forming regions and their phase dependence.
Our Drop in the Sea

- A study which would fully exploit the capabilities of modern (spectro-)interferometers and series of new (and old) spectroscopic and photometric observations is still missing.

- Our goals are:
  - Combination of observations from two different spectral regions - visible (NPOI, VEGA@CHARA) and infrared (MIRC@CHARA).
  - Improvement of the orbital inclination $i$ and the length of the ascending node $\Omega$.
  - To estimate sizes of the opaque objects by studying the continuum squared visibilities $V^2$.
  - Estimation of shapes and sizes of gaseous structures using toy models by studying the differential visibility $\Delta V$ and phase $\Delta \phi$.  

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**References**
THE HOARD

- β Lyrae was observed with three different instruments:
  - VEGA@CHARA [Mourard et al., 2009],
  - MIRC@CHARA [Monnier et al., 2006],
  - NPOI [Armstrong et al., 1998].

- The characteristics of VEGA@CHARA observations:
  - Four spectral bands:
  - \(V^2\) estimated for two sub-bands 10-20 nm wide, in each band.
  - Baselines ranging from 30 to 300 m.
  - The whole orbital period \(\approx 12.94\) d was covered during 9 nights.
  - Three spectral lines \(\lambda = \{\text{HI 656.2, HeI 667.8, HeI 706.5}\}\) nm.
THE SPATIAL COVERAGE
CONTINUUM RADIATION

- The continuum is emitted by the donor and the accretion disk.
- Orbital elements and extent of the opaque parts are known.
- Our goals:
  - Estimate the size of the opaque parts - disk height and radius and the polar radius of the donor.
  - Estimate luminosity of each component.
  - Try to put a constraint on the mass ratio.
  - Improve the elements determining the orientation on the sky.

Zhao+(2008)
CONTINUUM RADIATION II

- The tool SIMTOI [Kloppenborg and Baron, 2012b,a] is used to model the squared visibilities $V^2$:
  - The accretion disk is represented by a cylinder having the effective temperature $T_G$ and size $(R_G, H_G)$.
  - Donor has a Roche geometry, effective temperature $T_D$, the mass ratio $q$, the polar gravity and radius $\log g_{pole_D}^D, R_{pole_D}^D$.
  - Both objects are independent in SIMTOI - we have to fit more parameters, than we actually need to.
  - Contains several fitting environments, among those the MultiNest [Feroz and Hobson, 2008, Feroz et al., 2009, 2013):
    - A Bayesian fitting tool with robust uncertainty estimation.
    - Searches large portion of the parametric space, likely to find global minimum × time consuming.
CONTINUUM RADIATION III
CONTINUUM RADIATION IV

- Preliminary analysis:
  - All parameters cannot be fitted night-by-night.
  - Radiative properties (temperatures) are not well constrained by the data.
  - Properties cannot be estimated only from the interferometric data.
  - The data still contain some erroneous points.
The differential visibility $\Delta V$ and the differential phase $\Delta \phi$ variations along observed lines are studied. More complicated in lines, the model for both opaque and transparent parts is needed. A kinematic model is needed. A separate model is needed for each spectral line. Our objectives:

- Estimate the extent and the position of the gaseous structures.
- Estimate their velocity distribution.
- The models should be given by only few parameters.
SPECTRAL LINES II

► A tool developed by Anthony Meilland [Meilland et al., 2007, 2011] is being transcripted into Python and extended.

► The tool should be able to:
  ▶ Work with 3D models, both opaque and transparent.
  ▶ Support composite objects - stars with disks, binaries etc.
  ▶ Assign objects to orbits and their hierarchies.
  ▶ Compute observables - initially $V^2$, $\Delta V$, $\Delta \phi$ and $T_3 \phi$ - possibly also the flux $F$.
  ▶ Solve the inverse problem.
  ▶ Exploit the modularity and portability of Python language.
A SMALL DEMONSTRATION
A TASTE OF $\beta$ LYRAE I

- The differential visibility $\Delta V$ and phase variations $\Delta \phi$ - the arrows denote the baseline orientation.
A TASTE OF $\beta$ LYRAE II
THE CURRENT SIMPLE MODEL

- Discrepancies of the model:
  - First-order geometrical models:
    - The true structures similar to model.
    - More shapes have to be tested especially for jets and the hotspot.
  - There is not much physics behind the model:
    - Opaque objects are assigned flux fractions rather than temperatures or physical SEDs.
    - Radiation transfer is not solved within the transparent objects.
    - Hydrodynamics of the circumstellar gas is not solved.
  - A separate model is needed for each spectral line.
A LITTLE HELP

- Flux fractions:
  - Synthetic spectra representing disk and donor will be subtracted from an observed one to obtain the luminosity fraction of transparent parts.
OUTLOOK

► Work in progress:
  ▶ Continuum:
    ▶ The cylinder + Roche-lobe filling star is adequate model × radiative properties have to be constrained.
    ▶ Models containing hotspot or inhomogeneous temperature distribution have to be evaluated.
  ▶ Spectral lines:
    ▶ The model still lacks a lot of physics.
    ▶ Ready for estimation of the size and position gaseous structures.
  ▶ The tool:
    ▶ A fitting environment is to be attached - there is a large number of options - emcee, pyMultiNest, NLOPT.
    ▶ Development of the backend, to make its usage easier.
    ▶ Development of a more physical model.


