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

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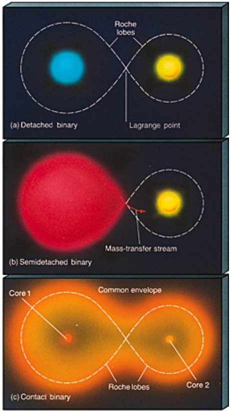
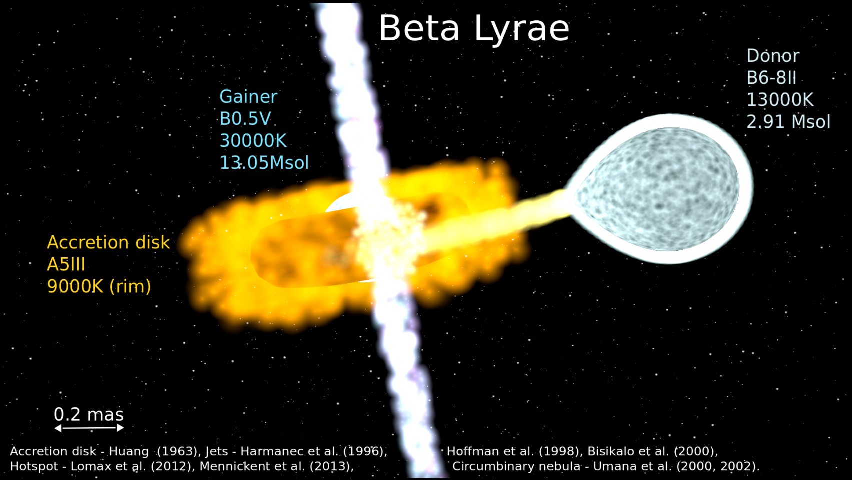
MASS TRANSFER IN BINARIES

- 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, $\mathrm{d}M/\mathrm{d}t \approx 10^{-5} - 10^{-6}\,\mathrm{M}_\odot.\mathrm{yr}^{-1}$, $\Delta T \approx 0.01 - 0.1\,\mathrm{Myr}$.
    - Slow one, conservative, $\mathrm{d}M/\mathrm{d}t \approx 10^{-7} - 10^{-9}\,\mathrm{M}_\odot.\mathrm{yr}^{-1}$, $\Delta T \approx 1 - 10\,\mathrm{Myr}$.
  - *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 s.yr^{-1} [Ak et al., 2007].
- *Most likely undergoing the rapid mass transfer phase*.


Beta Lyrae
Gainer
B0.5V
30000K
13.05Msol
Donor
B6-8II
13000K
2.91 Msol
Accretion disk
A5III
9000K (rim)
0.2 mas
Accretion disk - Huang (1963), Jets - Harmanec et al. (1996), Hoffman et al. (1998), Bisikalo et al. (2000),
Hotspot - Lomax et al. (2012), Mennickent et al. (2013), Circumbinary nebula - Umana et al. (2000, 2002).

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 β Lyrae in visible.
    - [Harmanec et al., 1996] - spectro-photo-interferometric study, jet-like structures detected.
    - [Umana et al., 2000, 2002] - radio nebula aligned with the jets revealed.
    - [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 Hα-forming regions at low resolution, jets were not detected.
    - [Bonneau and Chesneau et al., 2011] spectro-inteferometry with VEGA@CHARA in visible, line forming regions and their phase dependence.

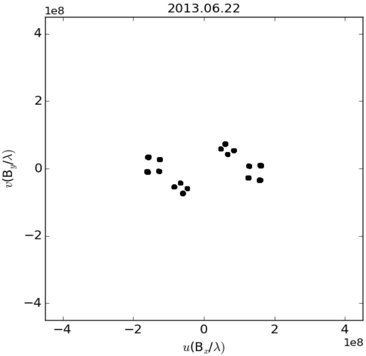
OUR DROP IN THE SEA

- 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 Ω.
  - 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 ΔV and phase $\Delta\phi$.

THE HOARD

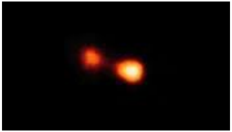
- β Lyrae was observed with three different instruments:
  - *VEGA@CHARA* [Mourard et al., 2009],
  - *MIRC@CHARA* [Monnier et al., 2006],
  - *NPOI* [Armstrong et al., 1998].
- The characteristics of VEGA@CHARA observations:
  - Four spectral bands: $\{520 - 550, 640 - 680, 685 - 725, 805 - 845\}$ nm.
  - 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 ≈ 12.94 d was covered during 9 nights.
  - Three spectral lines $\lambda = \{\mathrm{HI}\,656.2, \mathrm{HeI}\,667.8, \mathrm{HeI}\,706.5\}$ nm.

THE SPATIAL COVERAGE



CONTINUUM RADIATION I

- The continuum is emitted the donor and the accretion disk.
- Orbital elements and extent of the opaque parts is 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 determing the orientation on the sky.

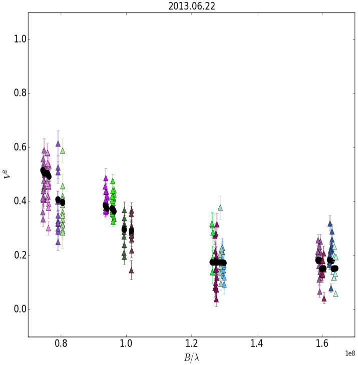


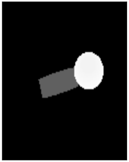
Zhao+(2008)

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 $T_{\rm G}$ and size $(R_{\rm G}, H_{\rm G})$.
  - Donor has a Roche geometry, effective temperature $T_{\rm D}$, the mass ratio q, the polar gravity and radius $\log g_{\rm D}^{\rm pole}, R_{\rm D}^{pole}$.
  - 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 $\times$ time consuming.

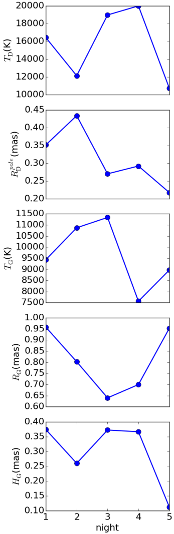
Continuum radiation III





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.



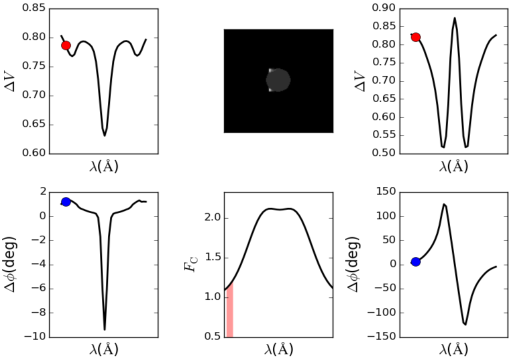
SPECTRAL LINES I

- The *differential visibility* ΔV 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

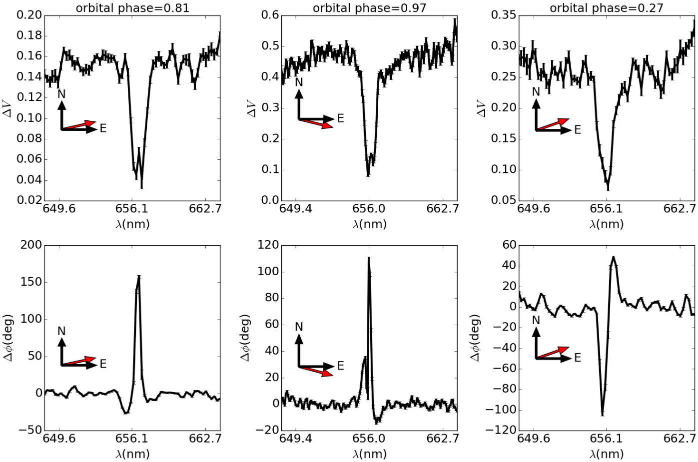
- A tool developed by Anthony Meilland [Meilland et al., 2007, 2011] is being transcripted into Python and extended.
- The tool should be able to:
  - Work with 3D models, both opaque and transparent.
  - Support composite objects - stars with disks, binaries etc.
  - Assign objects to orbits and their hierarchies.
  - Compute observables - initially V^2, ΔV, $\Delta\phi$ and $T_3\phi$ - possibly also the flux F.
  - Solve the inverse problem.
  - Exploit the modularity and portability of Python language.

A SMALL DEMONSTRATION

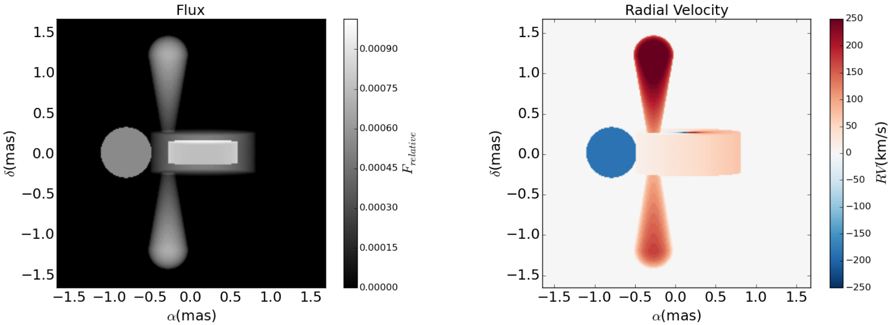


A TASTE OF β LYRAE I

- The differential visibility ΔV and phase variations $\Delta\phi$ - the arrows denote the baseline orientation.



A TASTE OF β LYRAE II

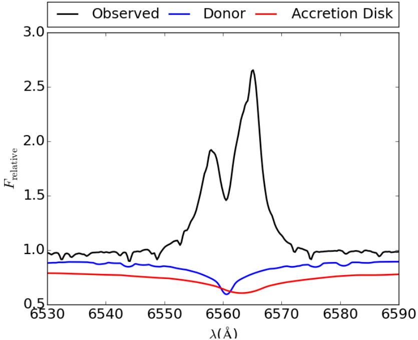


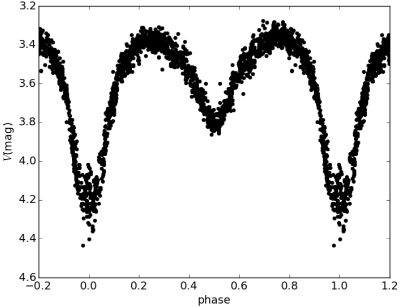
THE CURRENT SIMPLE MODEL

- 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 substracted 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 $\times$ 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.

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