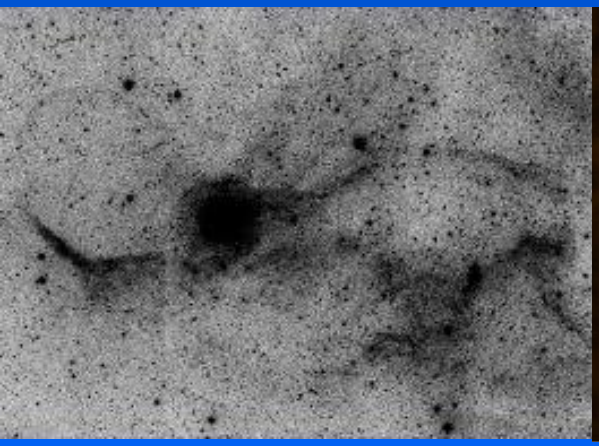
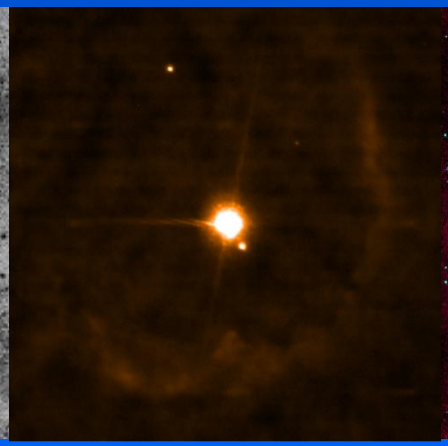
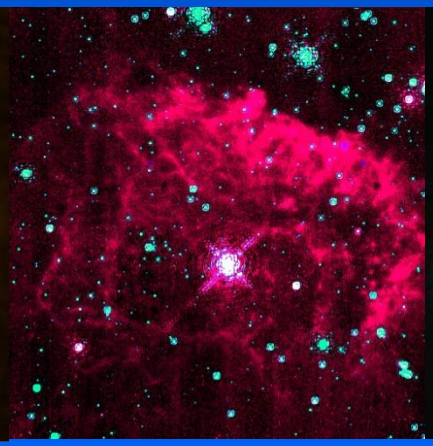
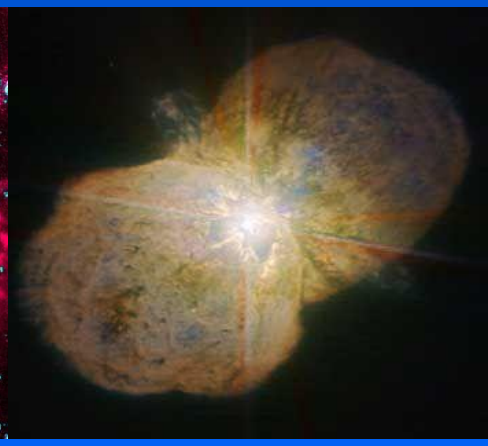
Modeling the Asymmetric Wind of the Luminous Blue Variable Binary MWC 314

A. Lobel[1], J. Groh[2], C. Martayan[3], Y. Frémat[1] , K. Torres Dozinel[4], G. Raskin[5], H. Van Winckel[5], S. Prins[5], W. Pessemier[5], C. Waelkens[5], H. Hensberge[1], L. Dumortier [1], A. Jorissen[6], S. Van Eck[6], H. Lehmann[7]

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Motivation

- Are there analogs of notorious LBV binary stars, i.e. like η Carinae? Long-term monitoring with HERMES of various (single) LBVs and candidate LBVs, searching for new LBV or cLBV binaries.

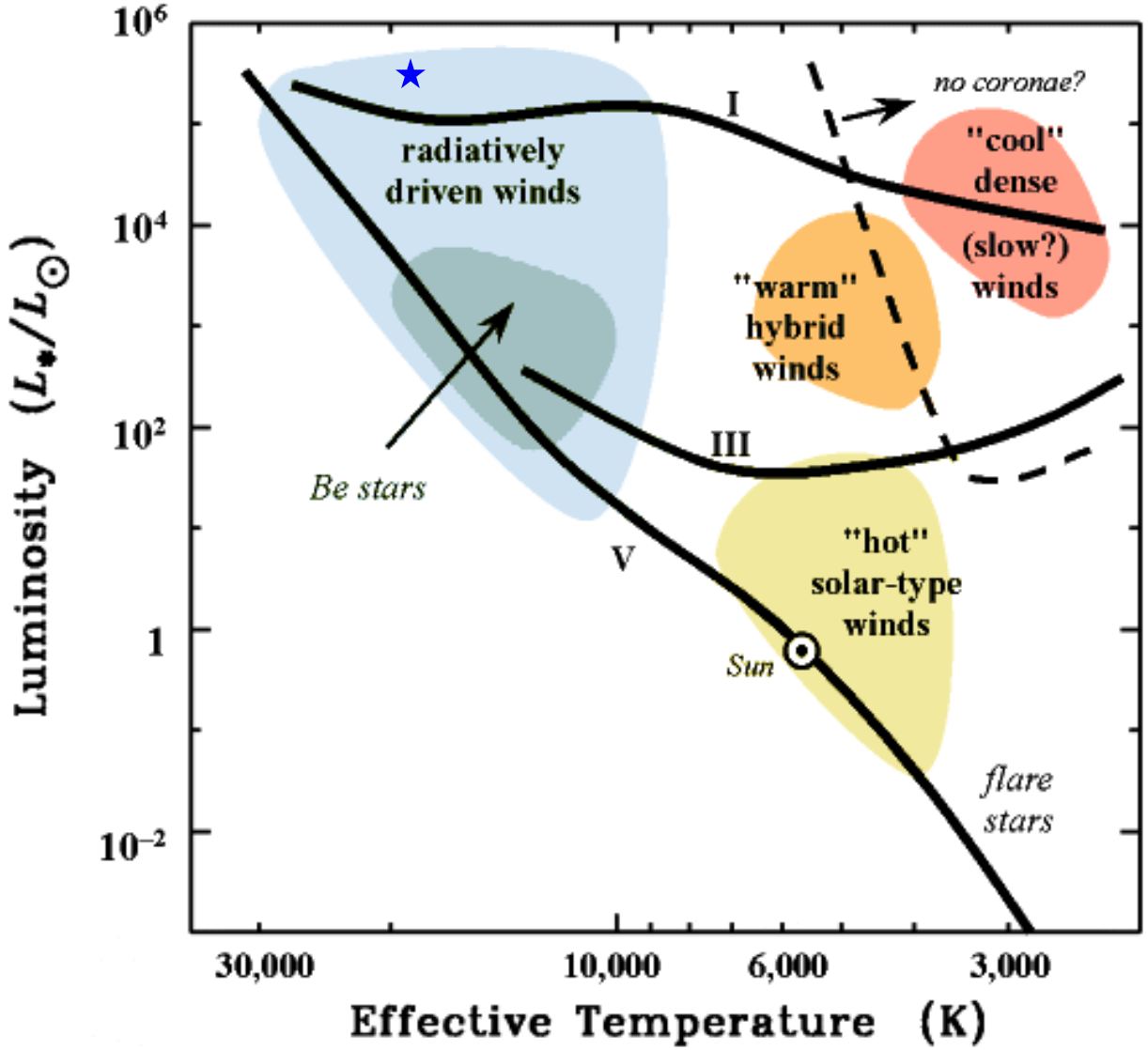
- MWC 314 is a very promising case because of its extended bipolar nebula and a possibility of being binary (P_{orb}~1 m).

- Determine accurate orbital elements of MWC 314. Provide evidence it is a massive binary instead of low-mass Be star. HERMES data reveals it is a semi-detached massive binary system with P_{orb}= 60.8 d.

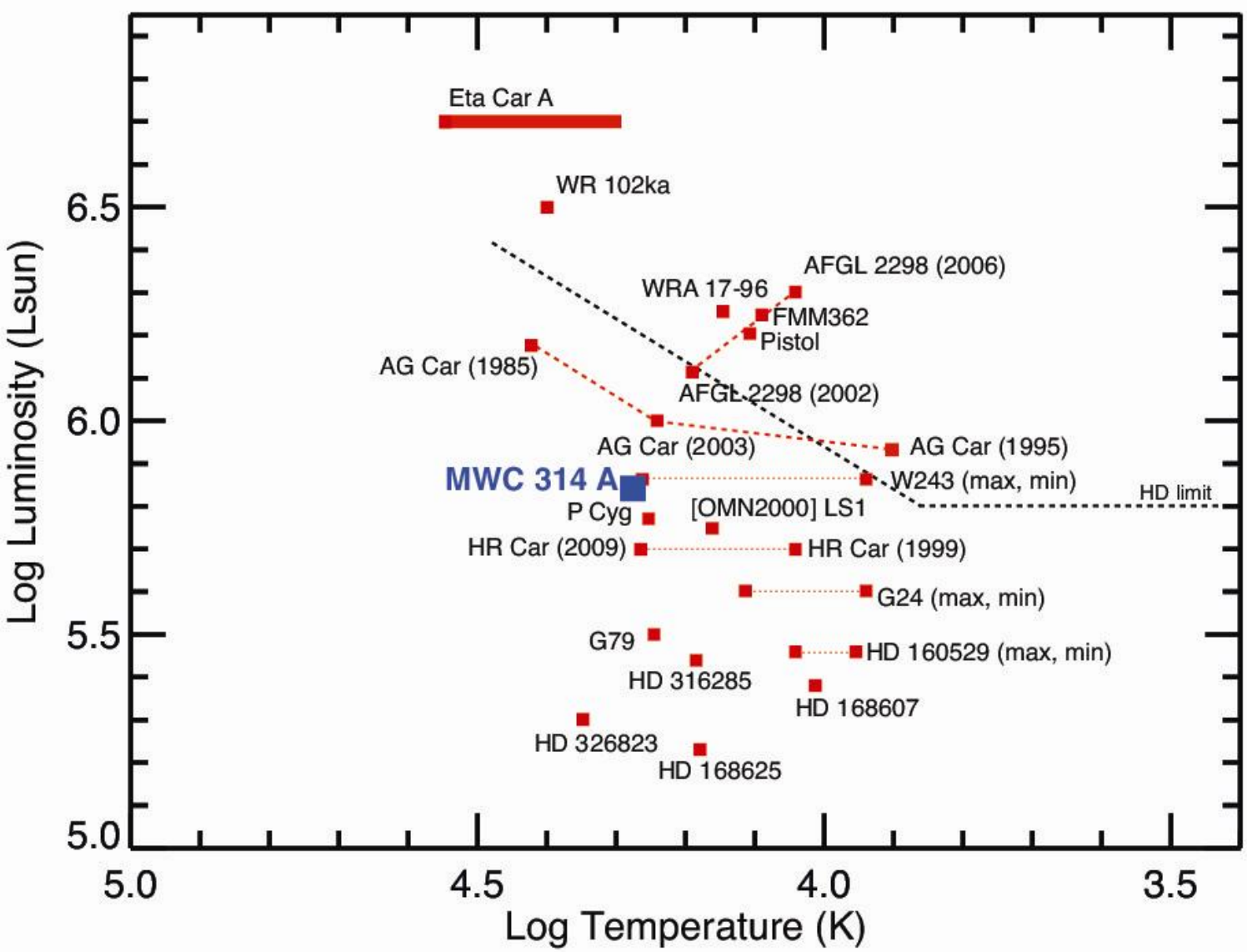
- Investigate and model quantitatively the asymmetric wind structure in MWC 314. Use advanced 3-D radiative transfer calculations with Wind3D to fit orbitally modulated optical He I P Cyg line profiles. Put strong contraints on wind-density and -velocity structure between binary components.

Luminous hot stars have radiatively driven winds

- accelerate very fast
- very broad UV absorption P Cyg wind lines
- large mass-loss rates
- very extended scattering winds



MWC 314 in the upper H-R diagram



MWC 314 was known Candidate LBV (Miroshnichenko et al., A&A 1998)

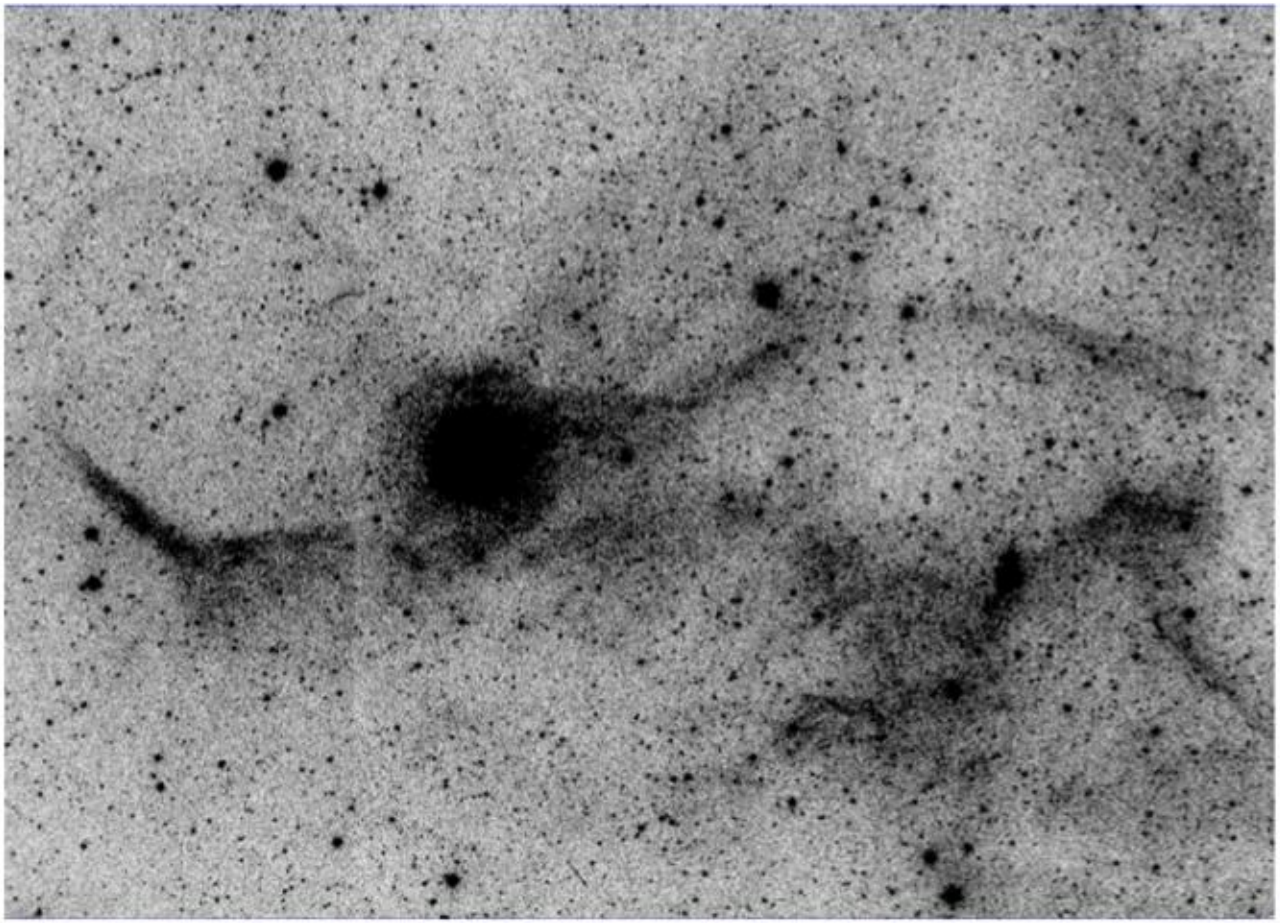
less-luminous B or luminous cLBV?

This work:

T_{eff} = 18000 K
log g = 2.26
$L_* / L_\odot$ = 5.8
$\dot{M}$ = 3 10^{-5} $M_\odot$ /yr

Very similar to true LBVs

Bi-polar Hα nebula of MWC 314



(Marston & McCollum A&A, 2008)

Fig. 1. Narrow band Hα image of the environments of MWC 314 showing the large east-west bipolar feature around the star. The figure is 12′.5 vertically. For all figures, north is up and east to the left.

Bi-polar Hα nebula of MWC 314

A. P. Marston and B. McCollum: Extended shells around B[e] stars 197

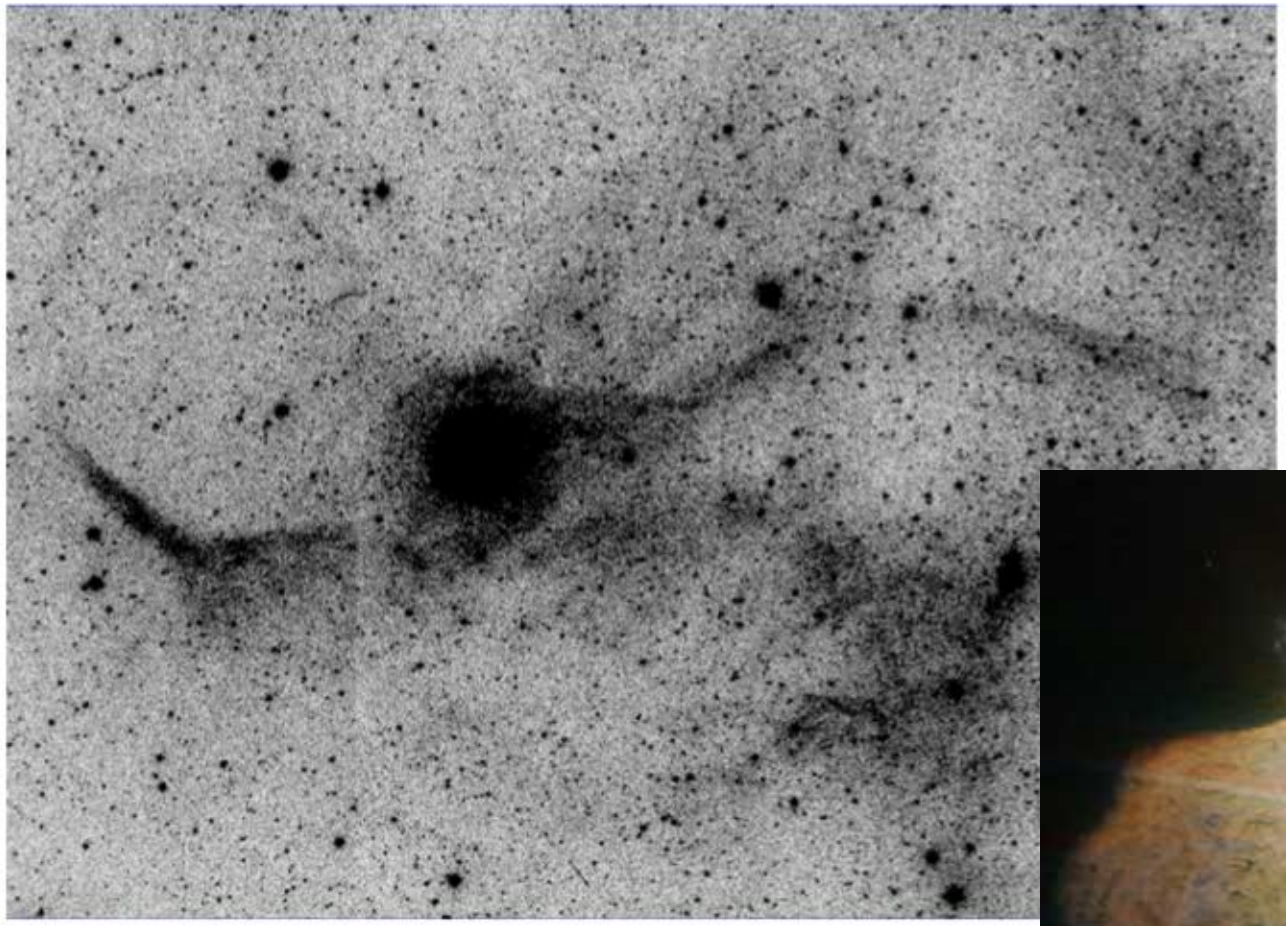
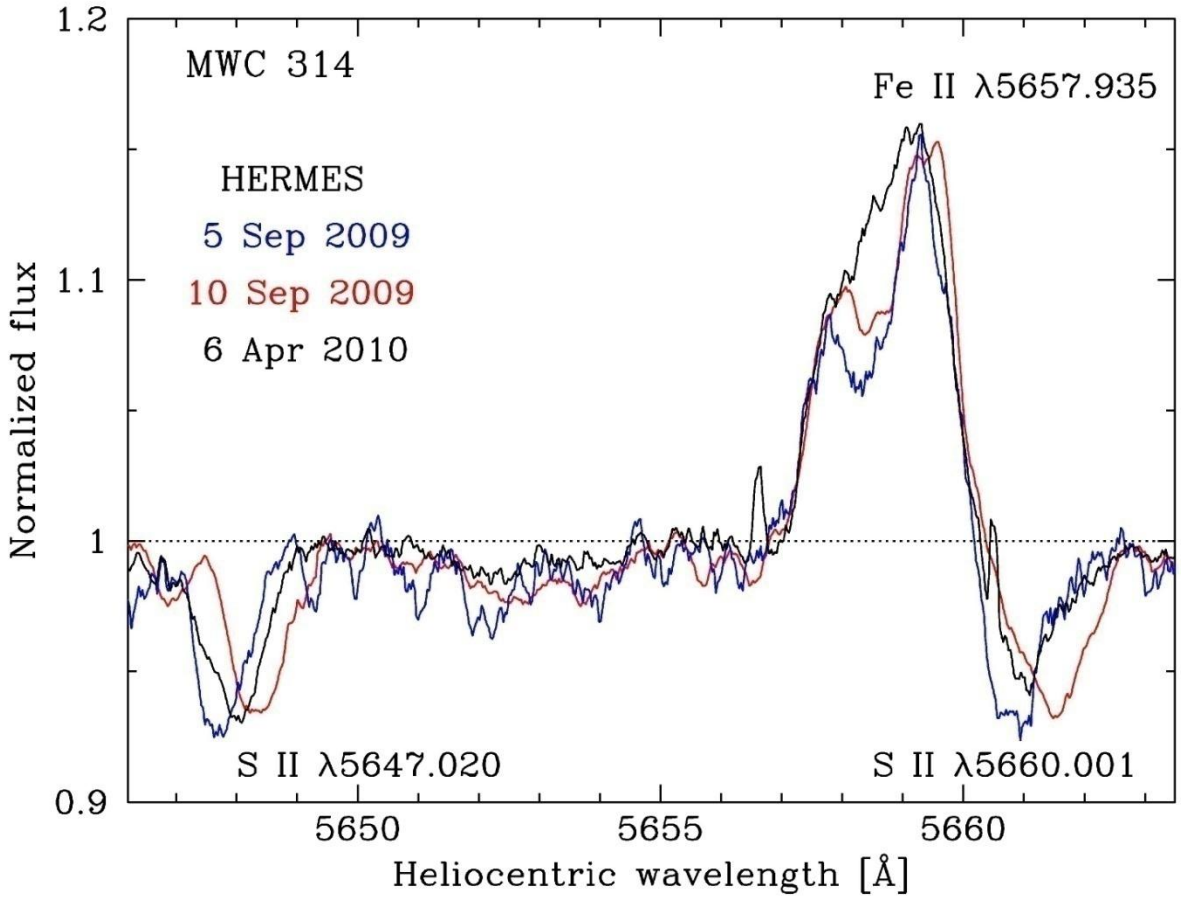


Fig. 1. Narrow band Hα image of the environments of MWC 314 showing the large east-west bipolar feature 12′.5 vertically. For all figures, north is up and east to the left.

(Marston & McCollum A&A, 2008)

η Carinae
LBV binary P_{orb}= 5.5 yr

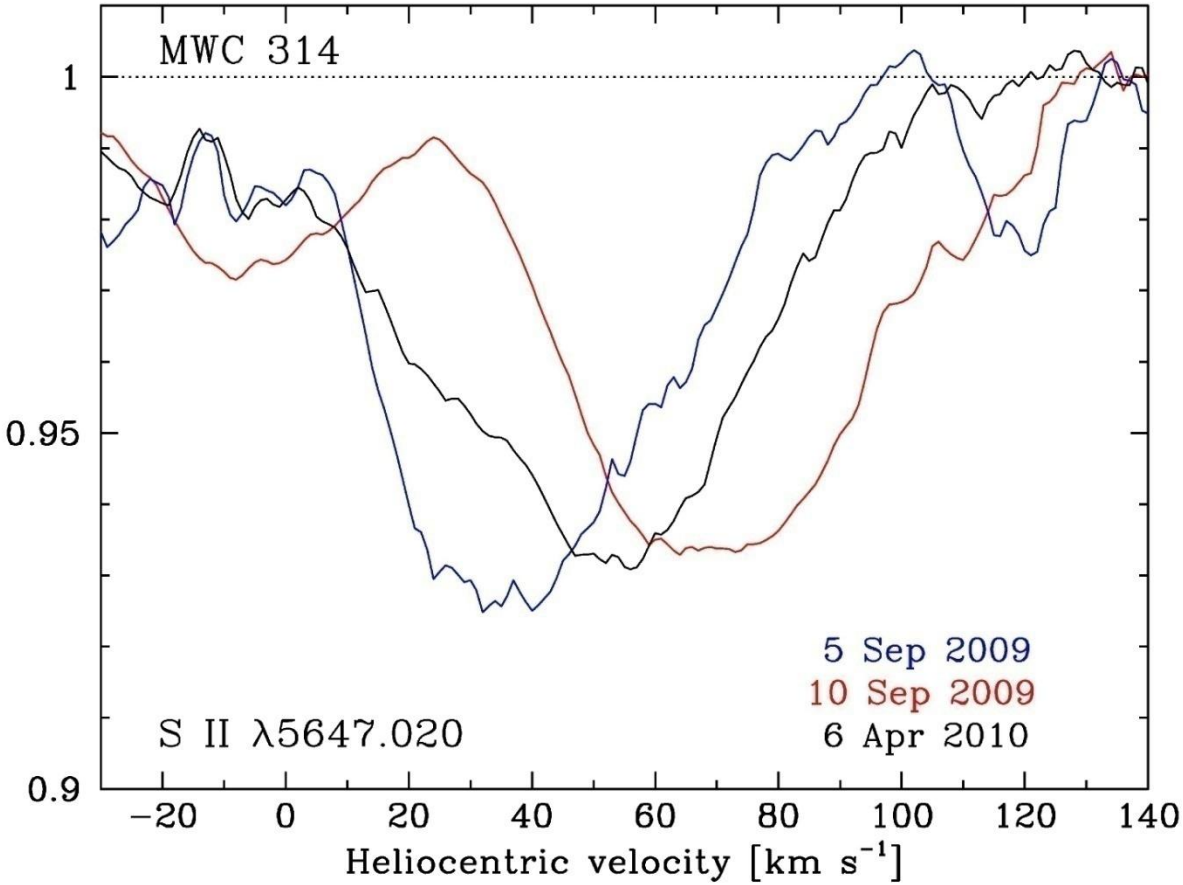
HERMES monitoring of LBV MWC 314



- **Very few known LBV binaries - Eta Car and Pistol Star(?) - MWC 314 orbital period of ~1 month determined from sparse observations over almost 6 years (Muratorio et al. A&A, 2008).**

⇒ HERMES monitoring program Sep 2009 – Aug 2011

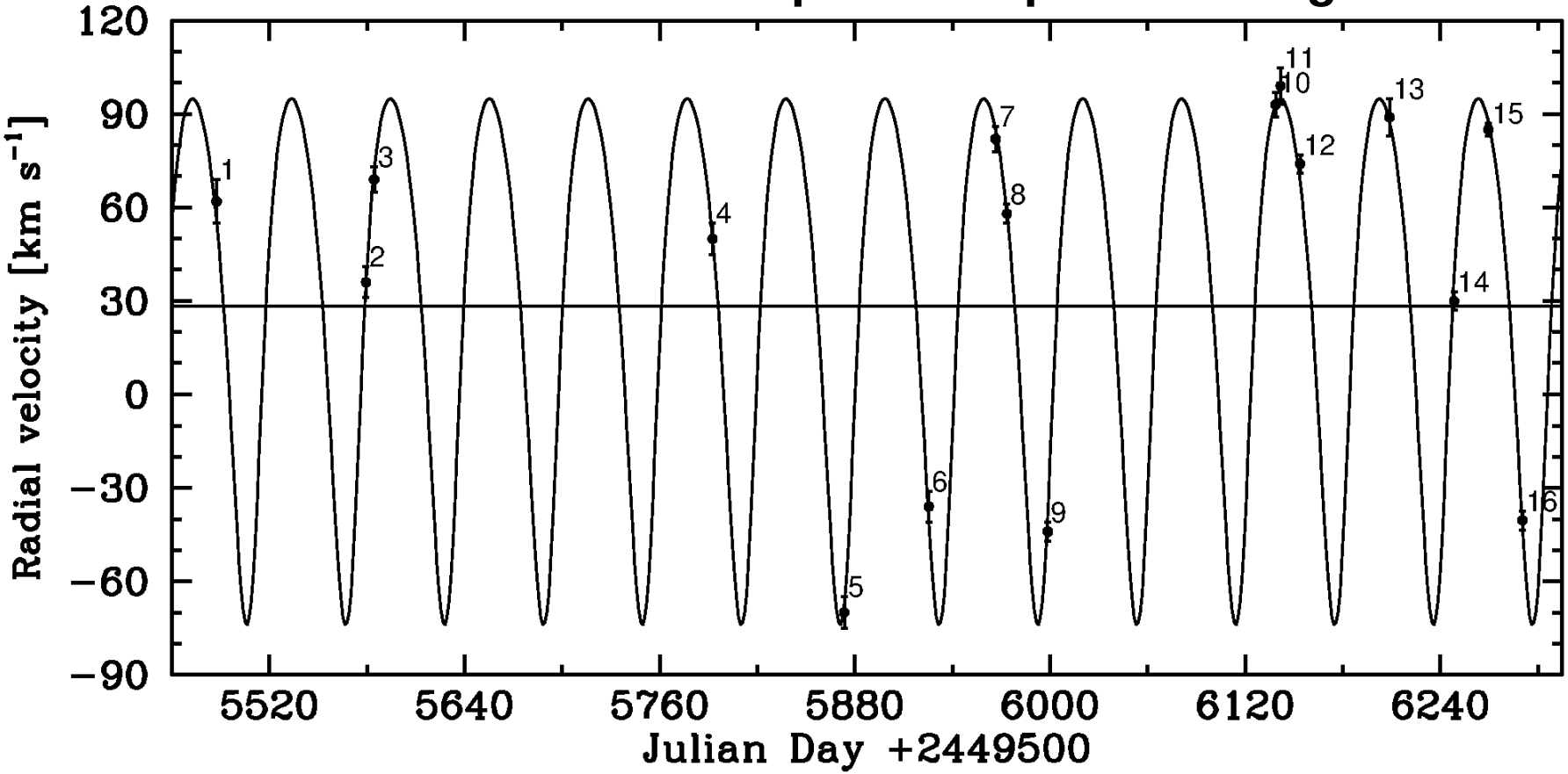
Feasibility study using the S II λ5647 line



Strong indication of binarity of MWC 314 from large RV shifts of ~33 km s^{-1} observed with HERMES over only 5 days in Sep 2009.

Radial velocity monitoring 2009-2011

- 1 ESO-FEROS spectrum June 2009
- 15 Mercator-HERMES spectra Sep 2009 – Aug 2011



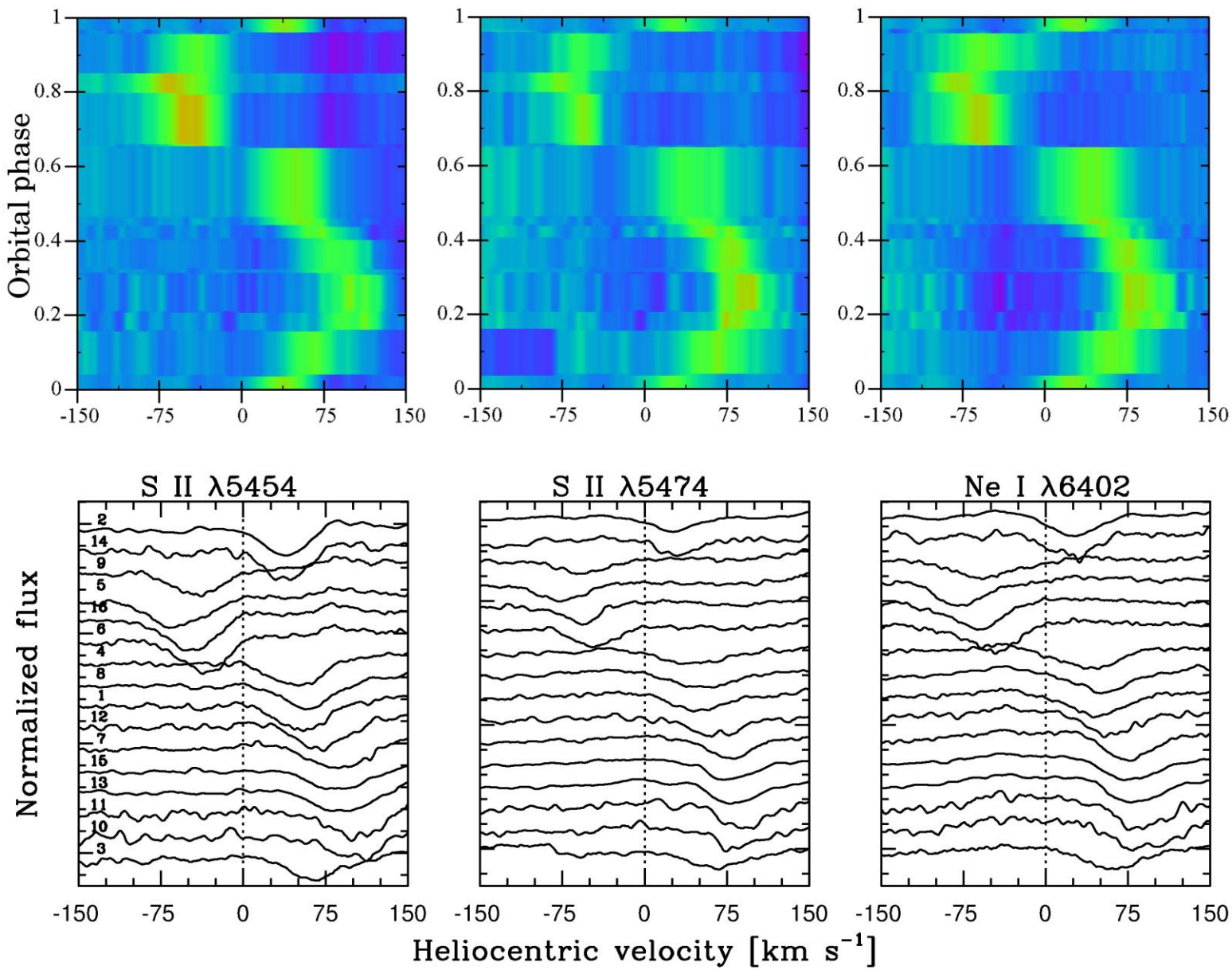
- Orbital solution: P_{orb} = 60.799 d

  e = 0.235 0.003

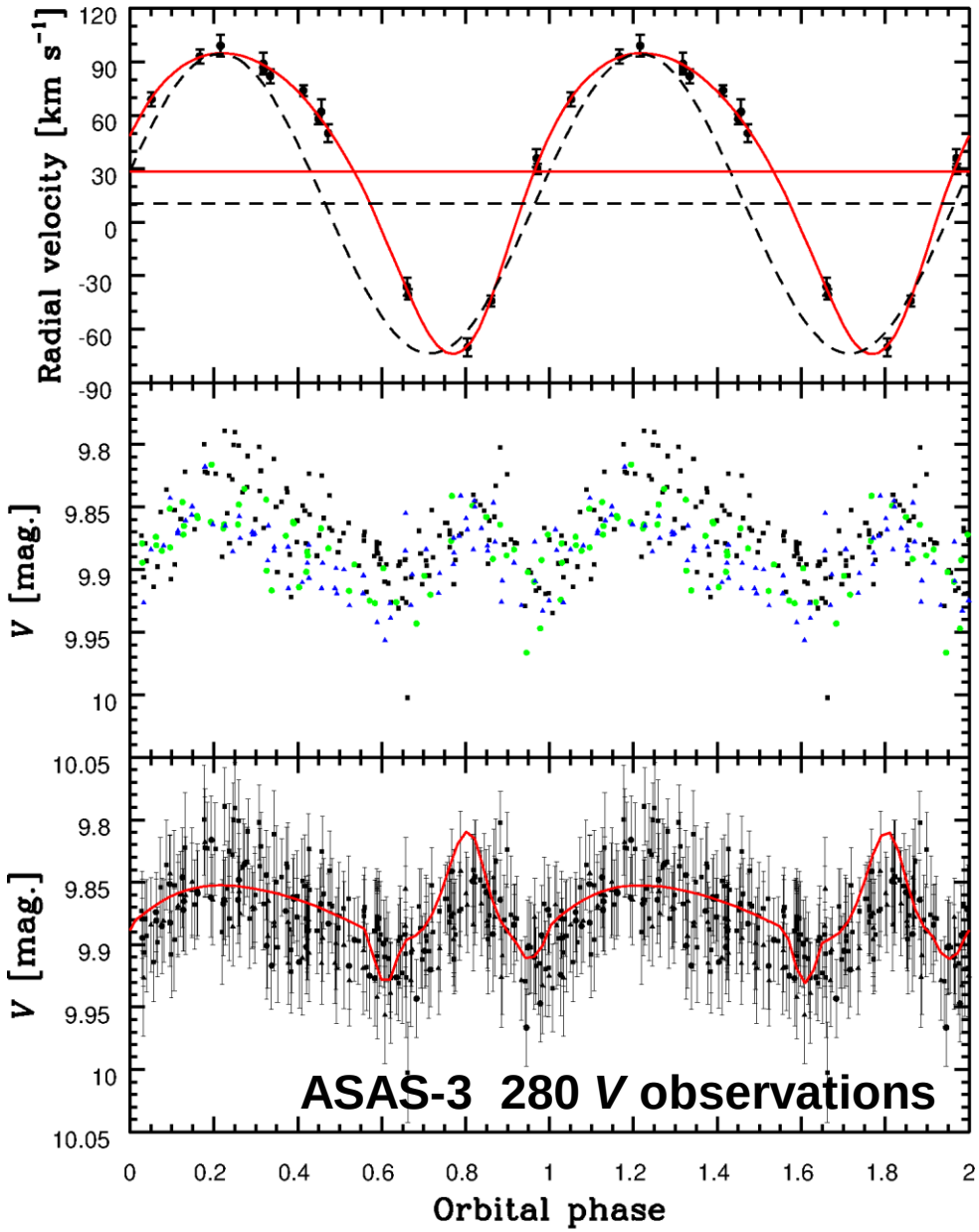
  i = 72.79 13.05 deg.

  a = 262.58 19.52 $R_\odot$

Photospheric absorption lines with orbital phase



Best fit of radial velocity- and *V*-curve



PHOEBE code
<u>combined best fit</u> of RV and *V*

MWC 314 is massive binary system with primary filling its Roche volume

***V*-curve shows partial eclipses for *i* = 72.79 13.05 deg.**

<u>Primary star:</u>

$T_{eff\,1}$ = 18000 K
M_1 = 39.66 4.3 $M_\odot$
R_1 = 86.80 $R_\odot$

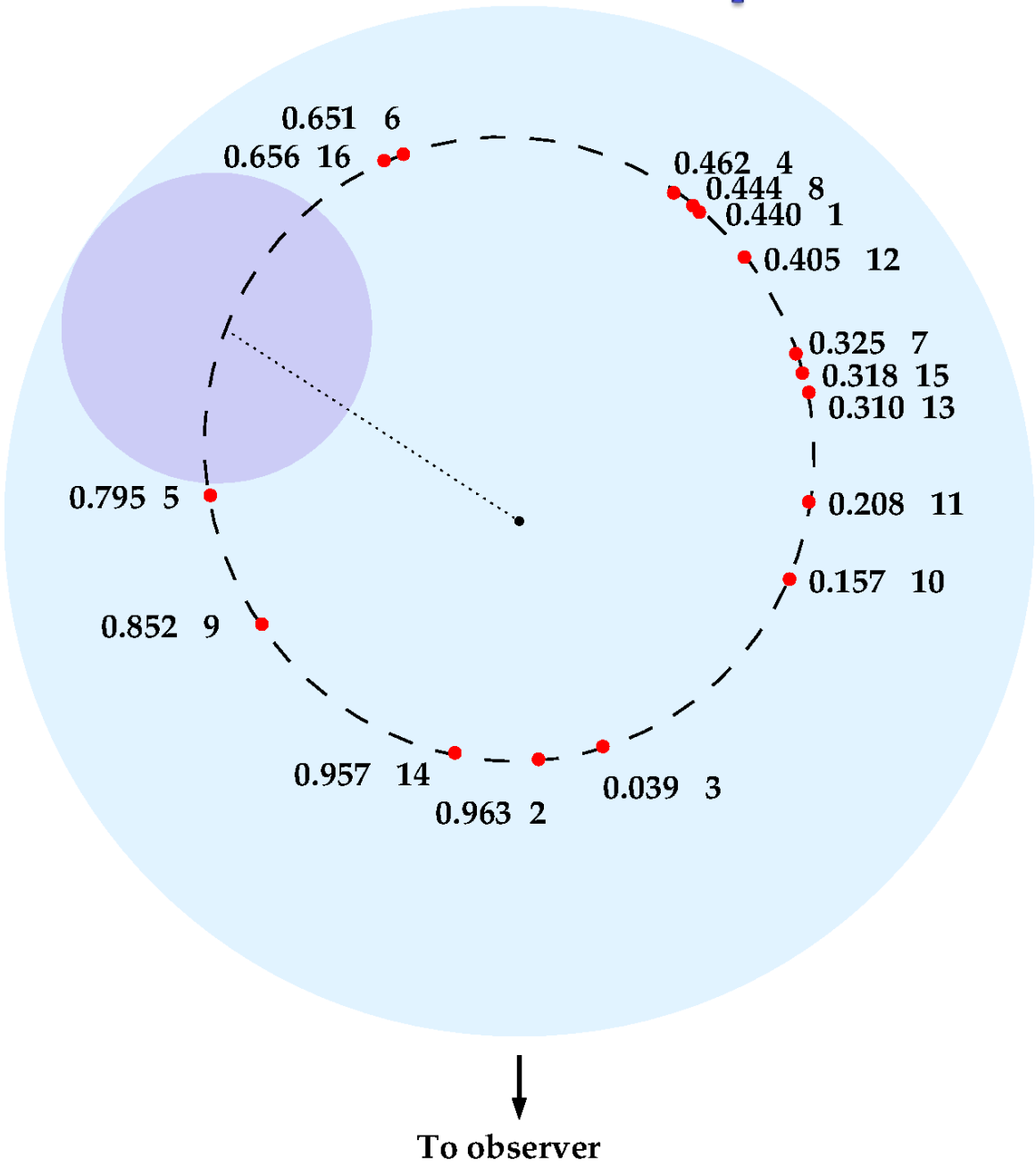
<u>Secondary star:</u>

$T_{eff\,2}$ = 6200 K
M_2 = 26.26 2.5 $M_\odot$
R_2 = 20.41 $R_\odot$

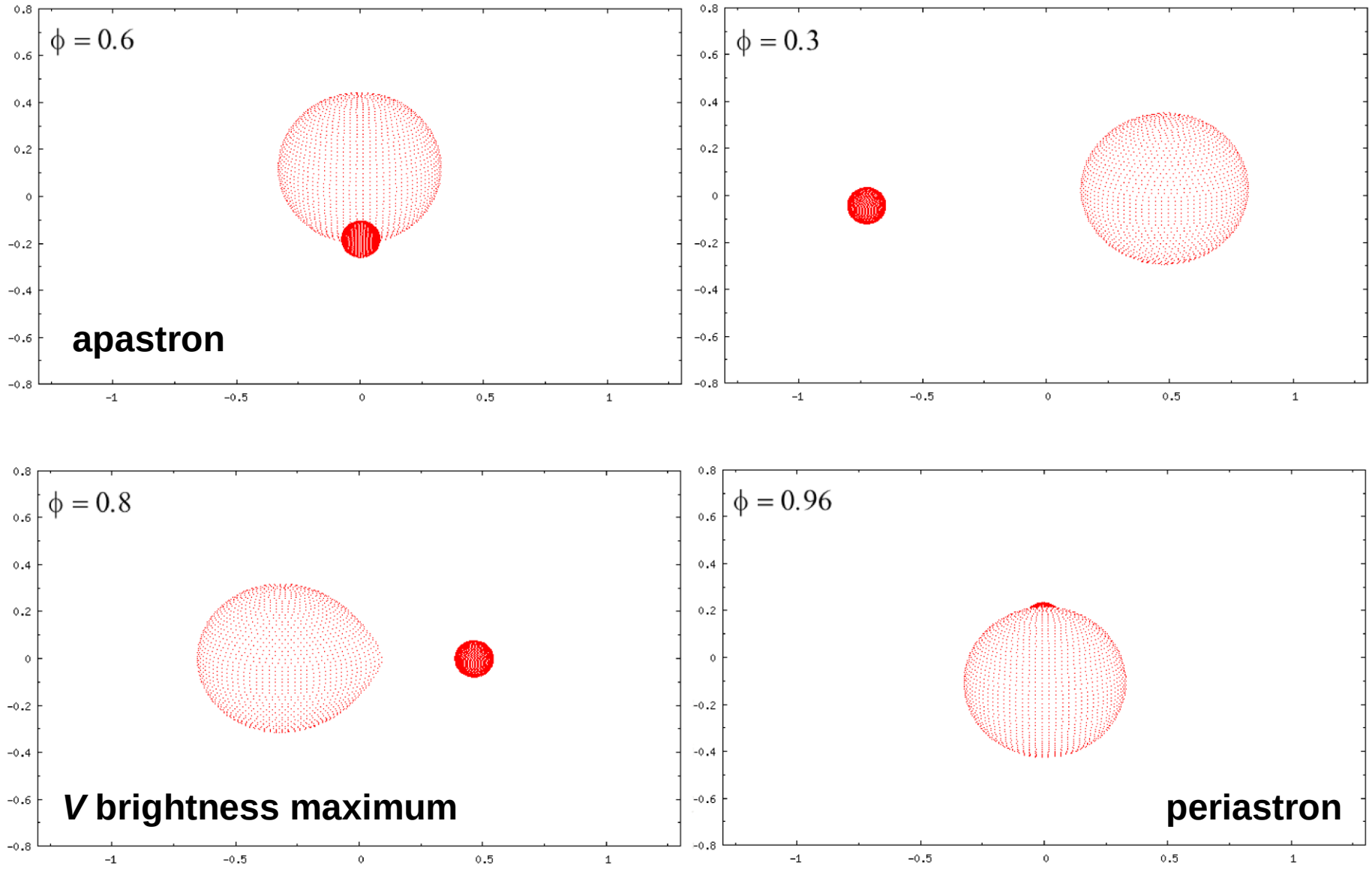
Observed orbital phases

$R_1 = 86.8\ R_\odot$

$a = 262.6\ R_\odot$



Primary star fills its Roche lobe



A&A Preprints:
http://dx.doi.org/10.1051/0004-6361/201220421

Astronomy & Astrophysics manuscript no. AA20421
July 1, 2013

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Received;

ABSTRACT

Aims. We present a spectroscopic analysis of MWC 314, a Luminous Blue Variable candidate with an extended bi-polar nebula. The detailed spectroscopic variability is investigated to determine if MWC 314 is a massive binary system with a supersonically accelerating wind, or a low-mass B[e] star. We compare the spectrum and spectral energy distribution to other LBVs (such as P Cyg) and find very similar physical wind properties, indicating strong kinship.
Methods. We combine long-term high-resolution optical spectroscopic monitoring and V-band photometric observations for determining the orbital elements and stellar parameters, and to investigate the spectral variability with the orbital phases. We develop an advanced model of the large-scale wind-velocity and -density structure with 3-D radiative transfer calculations that fit the orbitally modulated P Cyg profile of He I λ5876, showing outflow velocities above 1000 km s^{-1}.
Results. We find that MWC 314 is a massive semi-detached binary system of $\simeq$1.22 AU observed at an inclination angle of i=72.8° with an orbital period of 60.8 d and e=0.23. The primary star is a low-$v$sin$i$ LBV candidate of m_1=39.6 M$_\odot$ and R_1=86.8 R$_\odot$. The detailed radiative transfer fits show that the geometry of wind density is asymmetric around the primary star with increased wind density, by a factor of 3.3, leading the orbit of the primary. The variable orientation causes the orbital modulation observed in absorption portions of P Cyg wind lines. Wind accretion in the system produces a circumbinary disc.
Conclusions. MWC 314 is in a crucial evolutionary phase of close binary systems, when the massive primary star has its H envelope being stripped and is losing mass to a circumbinary disk. MWC 314 is a key system for studying the evolutionary consequences of these effects.

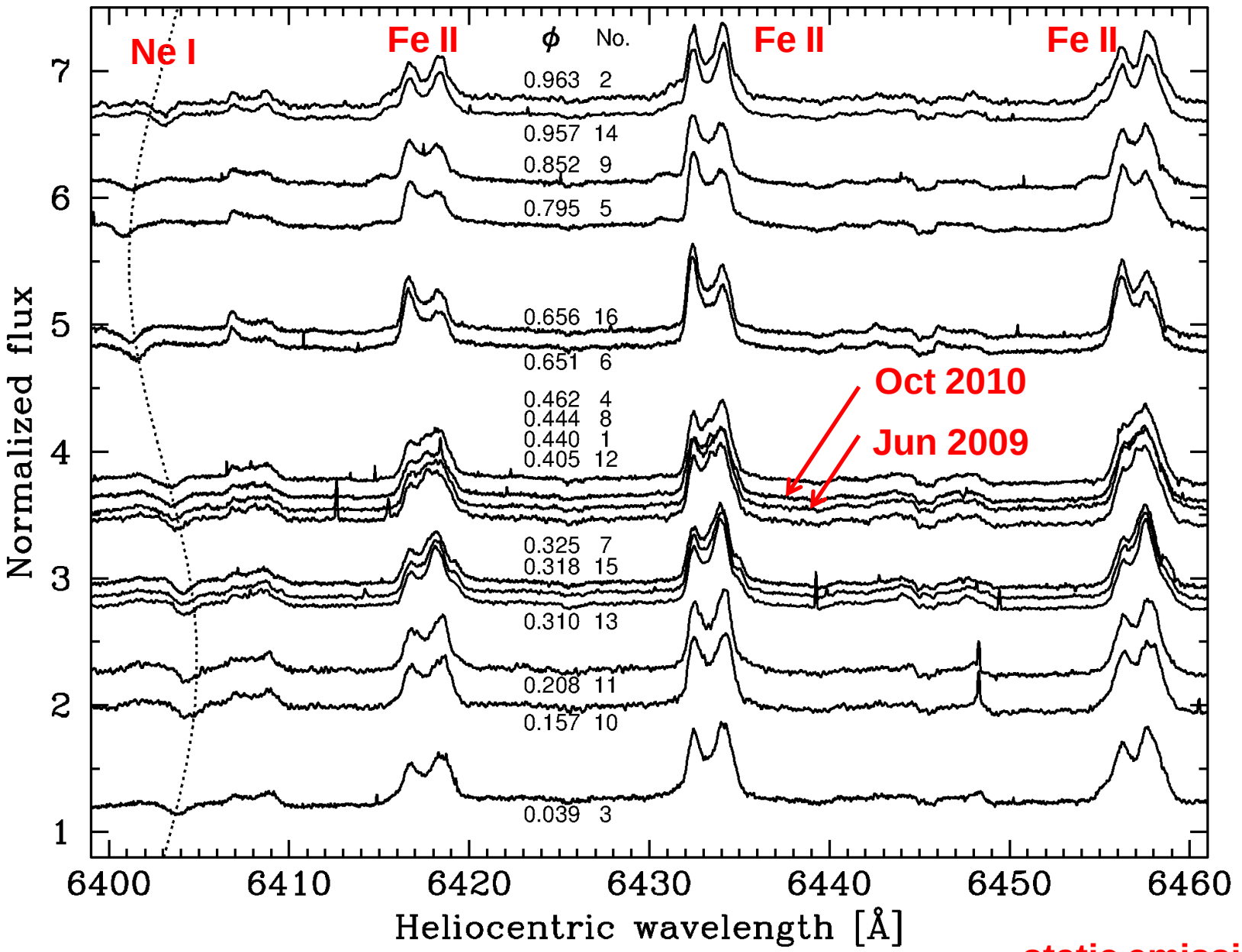
Key words. Stars: emission-line, Be – Stars: massive – Stars: binaries: spectroscopic – Stars: winds, outflows – Line: profiles – Radiative transfer – Accretion, accretion discs

1. Introduction

There is currently little known about the wind physics of the most massive binary stars. Although massive binary systems have been investigated for decades it is notoriously difficult to infer important wind properties, such as accurate mass-loss rates, wind driving and wind structuring mechanisms from traditional spectroscopic and photometric observations. Ultraviolet spectroscopy is one of the main sources for information about mas-

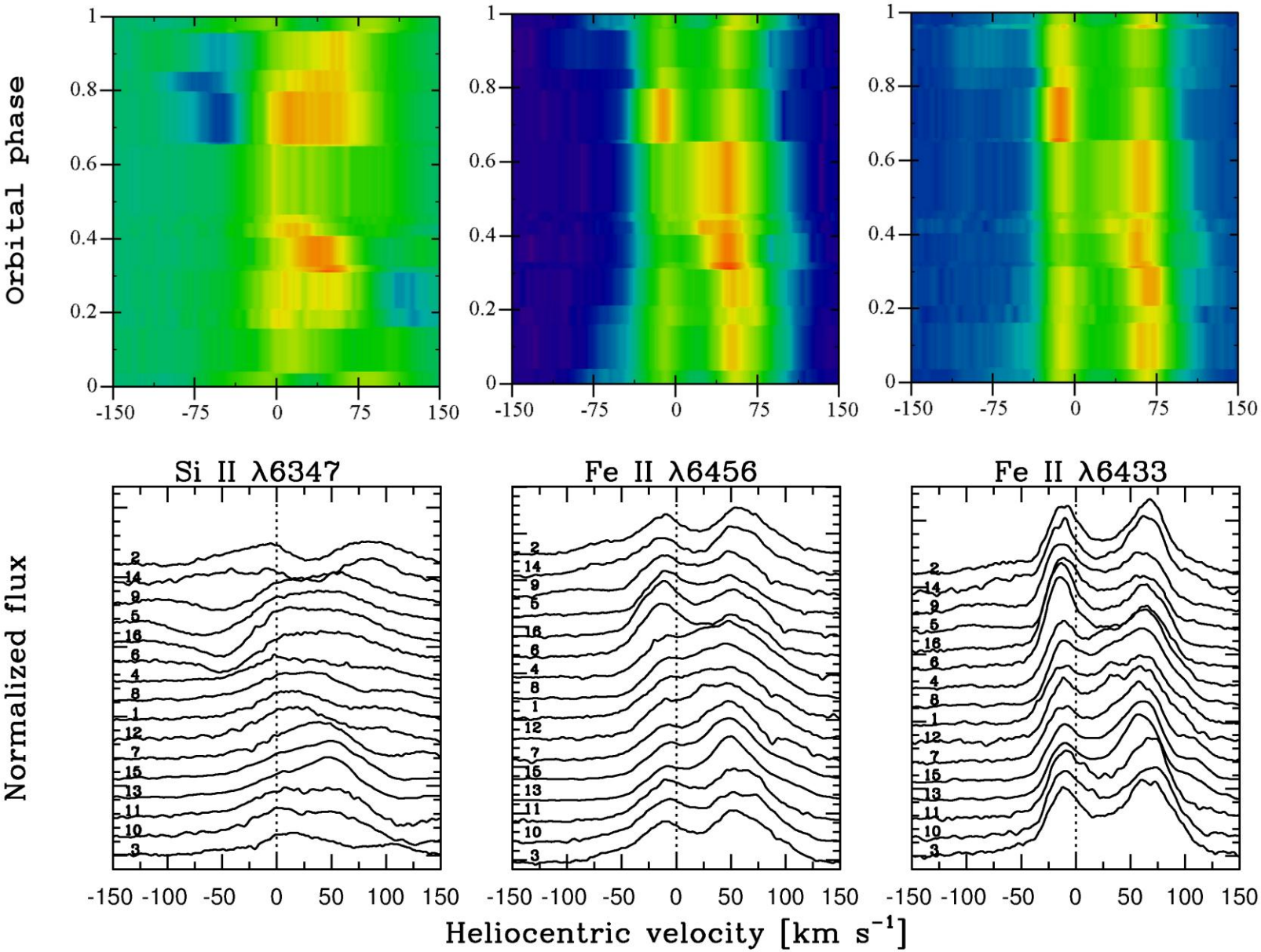
of the most luminous stars in the Galaxy by Miroshnichenko et al. (1998) with log($L_\star/L_\odot$)≃6.1±0.3, $T_{\rm eff}$≃20 to 30 kK, and $\dot{M}$∼ 3 10^{-5} M$_\odot$ yr^{-1} (assuming a single star). More recently, Muratorio et al. (2008) found that the star is a (possible) binary system with an orbital period of ∼30 d, however without determining other orbital parameters. Marston & McCollum (2008) demonstrated the presence of an extended double-lobe Hα-emission (bi-polar) nebula, or a large East-West bi-polar feature >13 pc (end to end) around the star. They suggest that the

Orbital modulation of optical emission lines



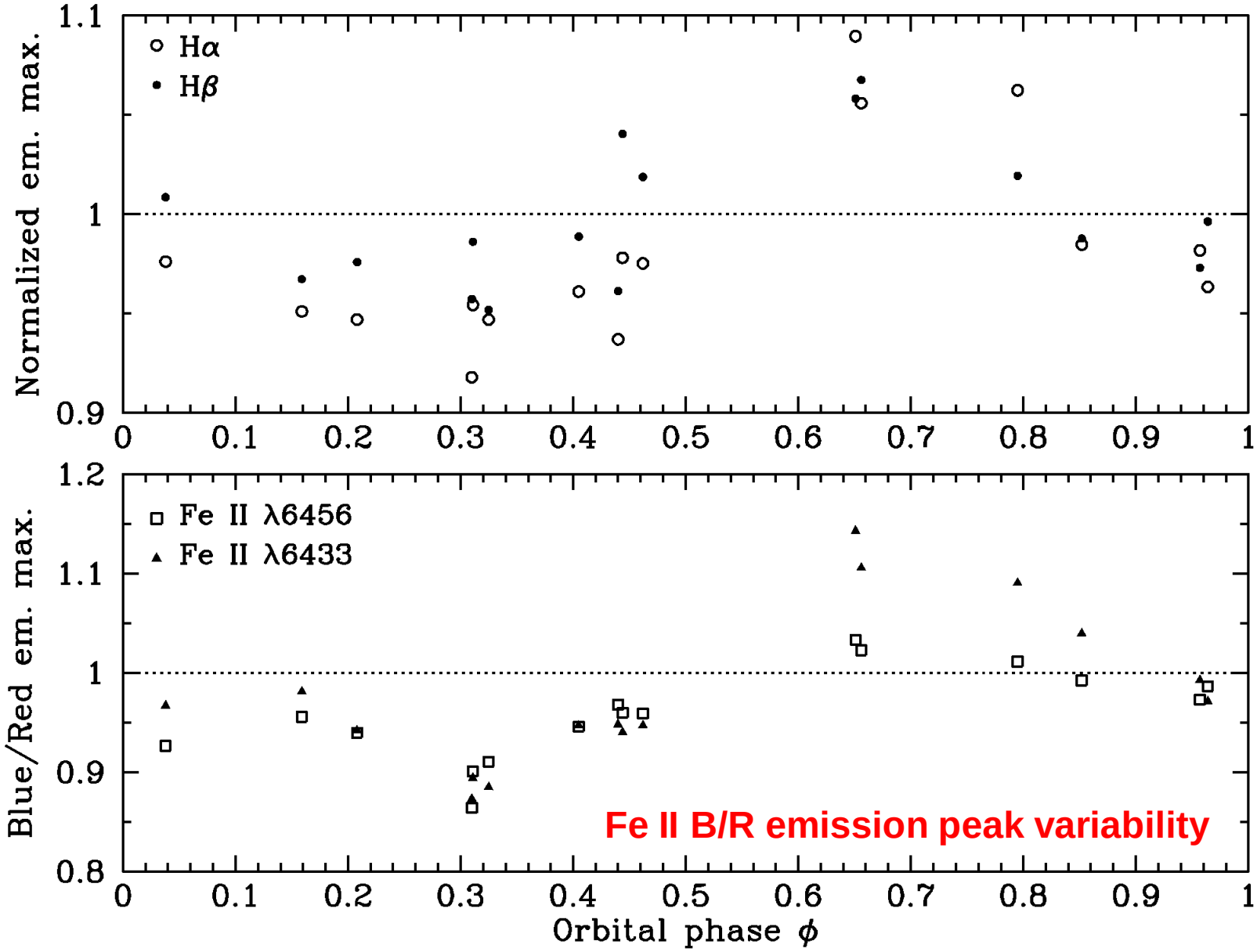
static emission lines

Double-peaked metallic emission lines



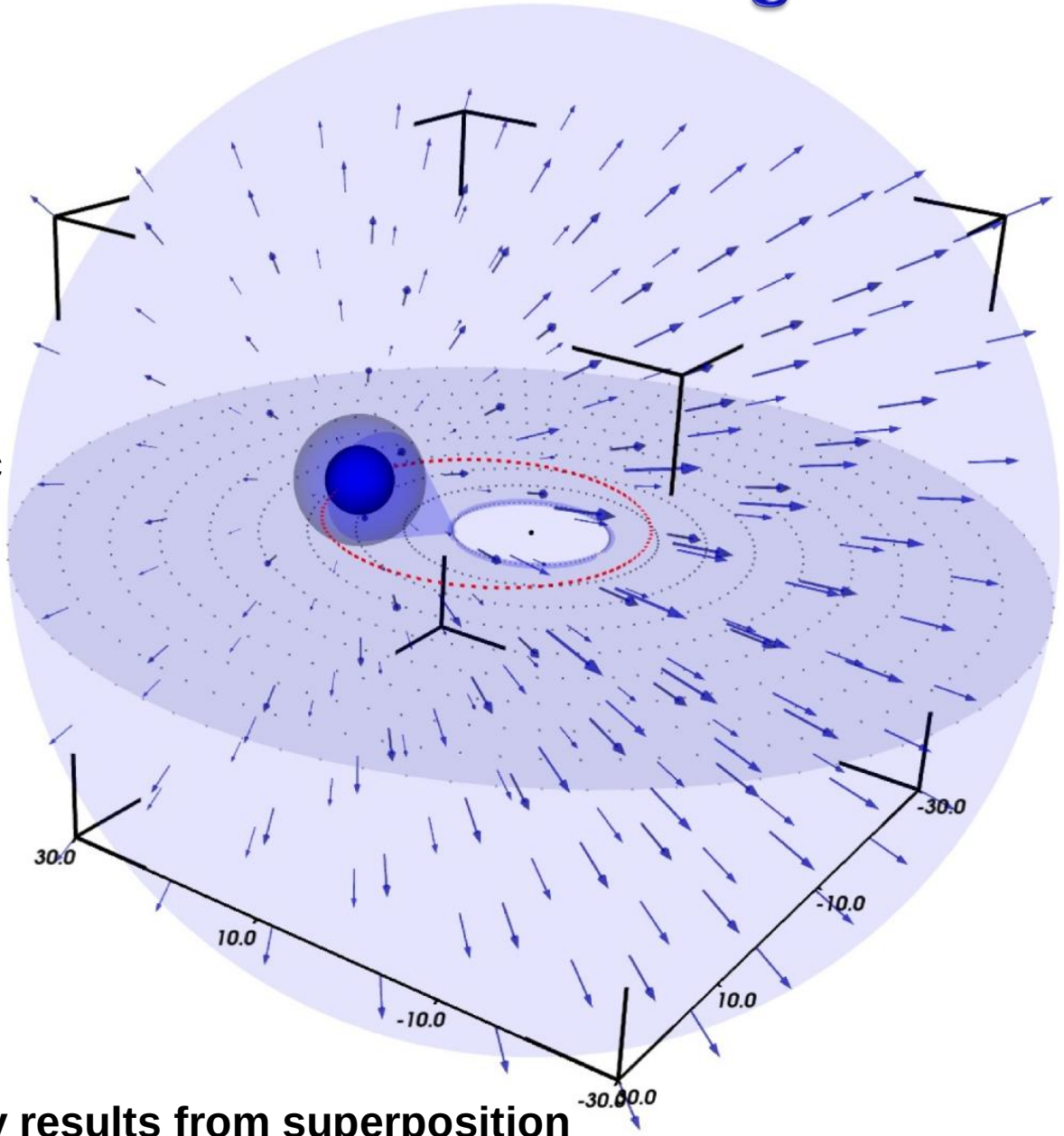
B/R emission peak variability with ϕ

Orbital variability of B/R emission maxima



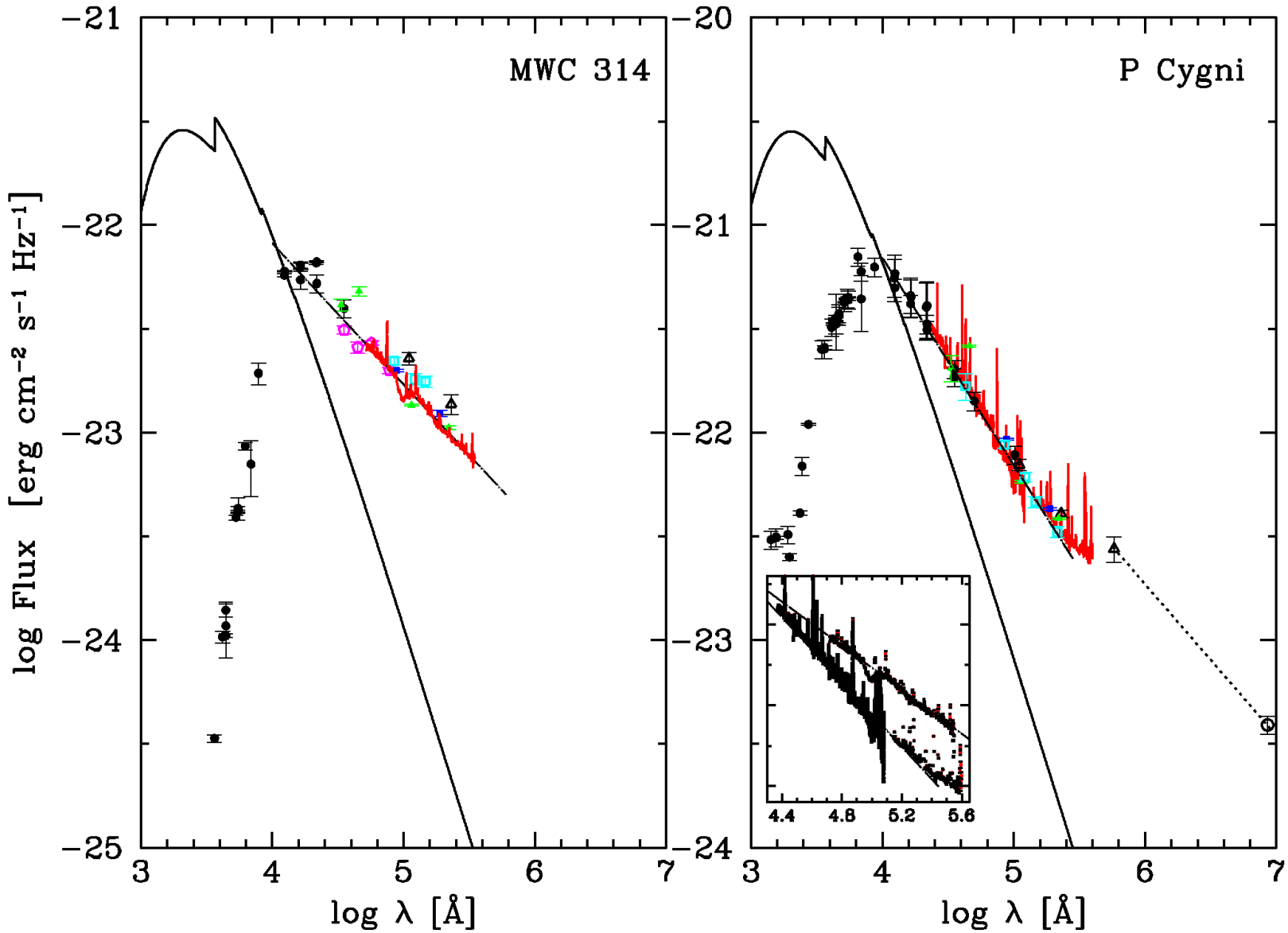
Emission line formation region

Double peaked metallic emission lines form in rotating circumbinary disc.



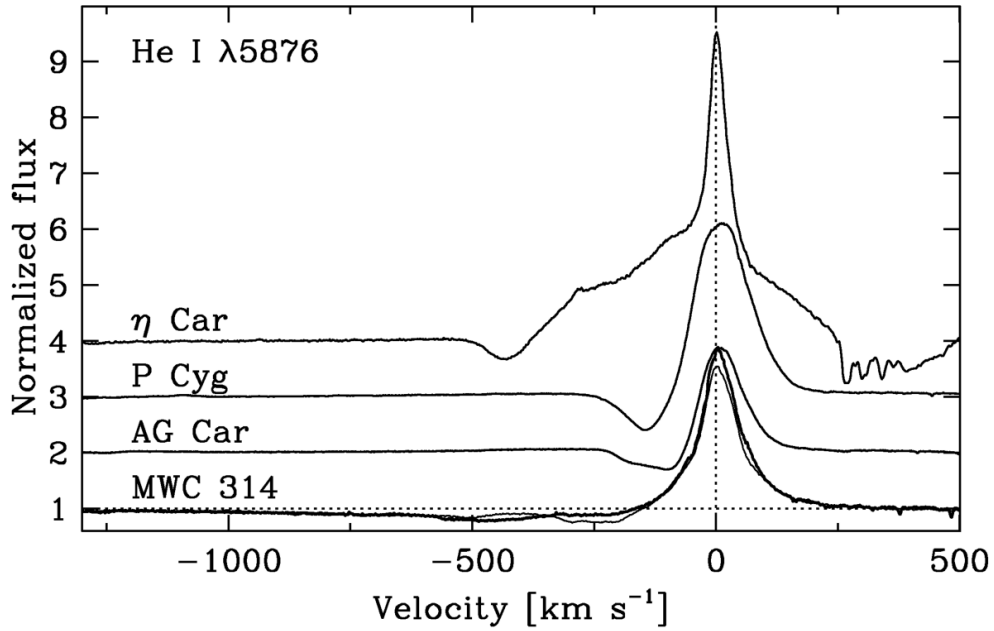
B/R em. peak variability results from superposition with wind absorption formed around primary.

SED comparison of MWC 314 and LBV P Cygni

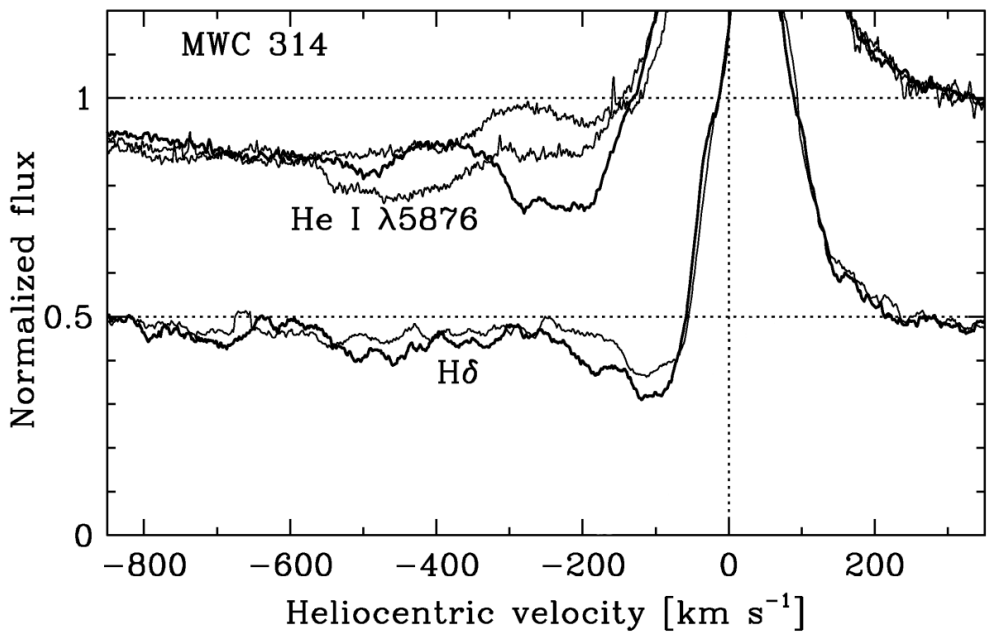


- **MWC 314 and P Cygni show very similar SEDs and IR free-free emission.**
- **Signaling very similar radial wind structures following a r^{-2} dependence.**

Comparison of He I λ5876 in LBVs



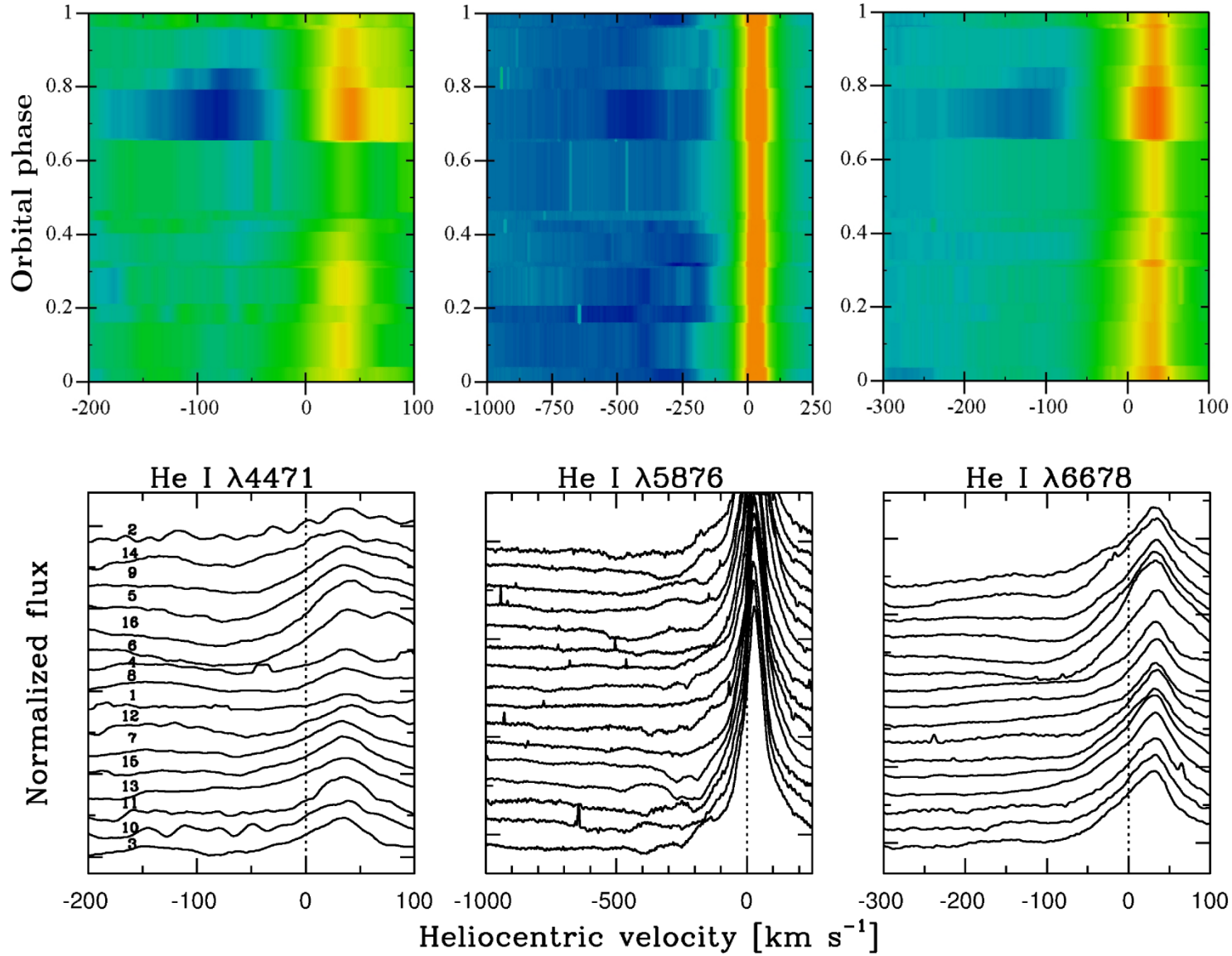
He I P Cyg profiles in MWC 314 with v_∞ > 1200 km/s.



Orbitally modulated strong changes in wind absorption for v_{wind} < 600 km/s.

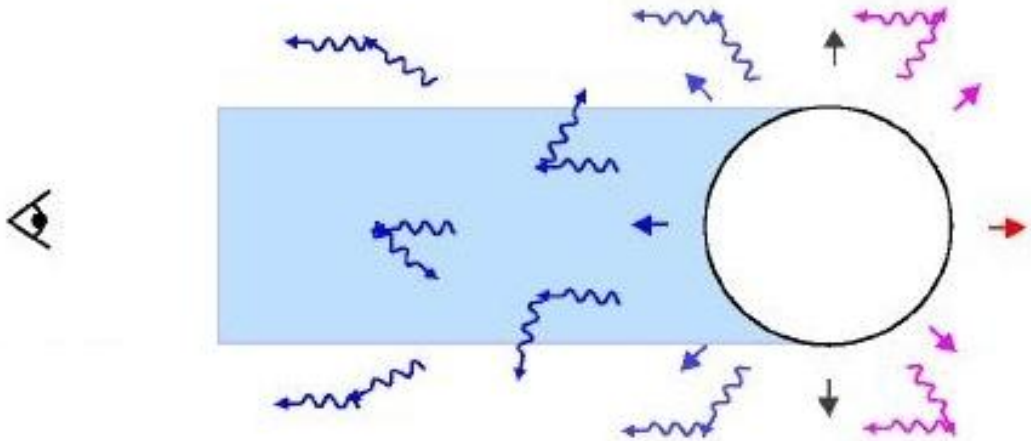
Also observed in the high H Balmer lines.

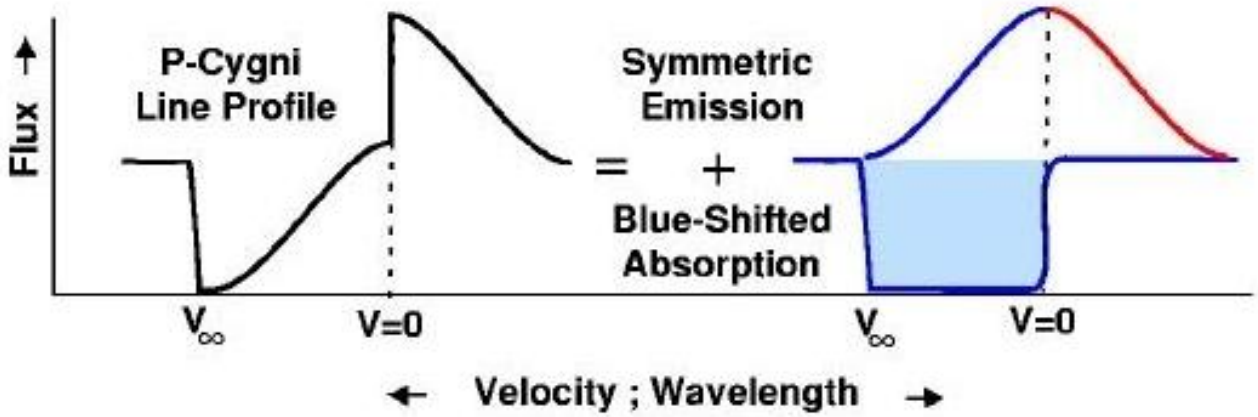
Orbital variability of He I lines in MWC 314



- **All He I lines show orbitally modulated wind absorption.**
- **Maximum wind absorption around ϕ = 0.65 – 0.85, or max. RV blueshift.**

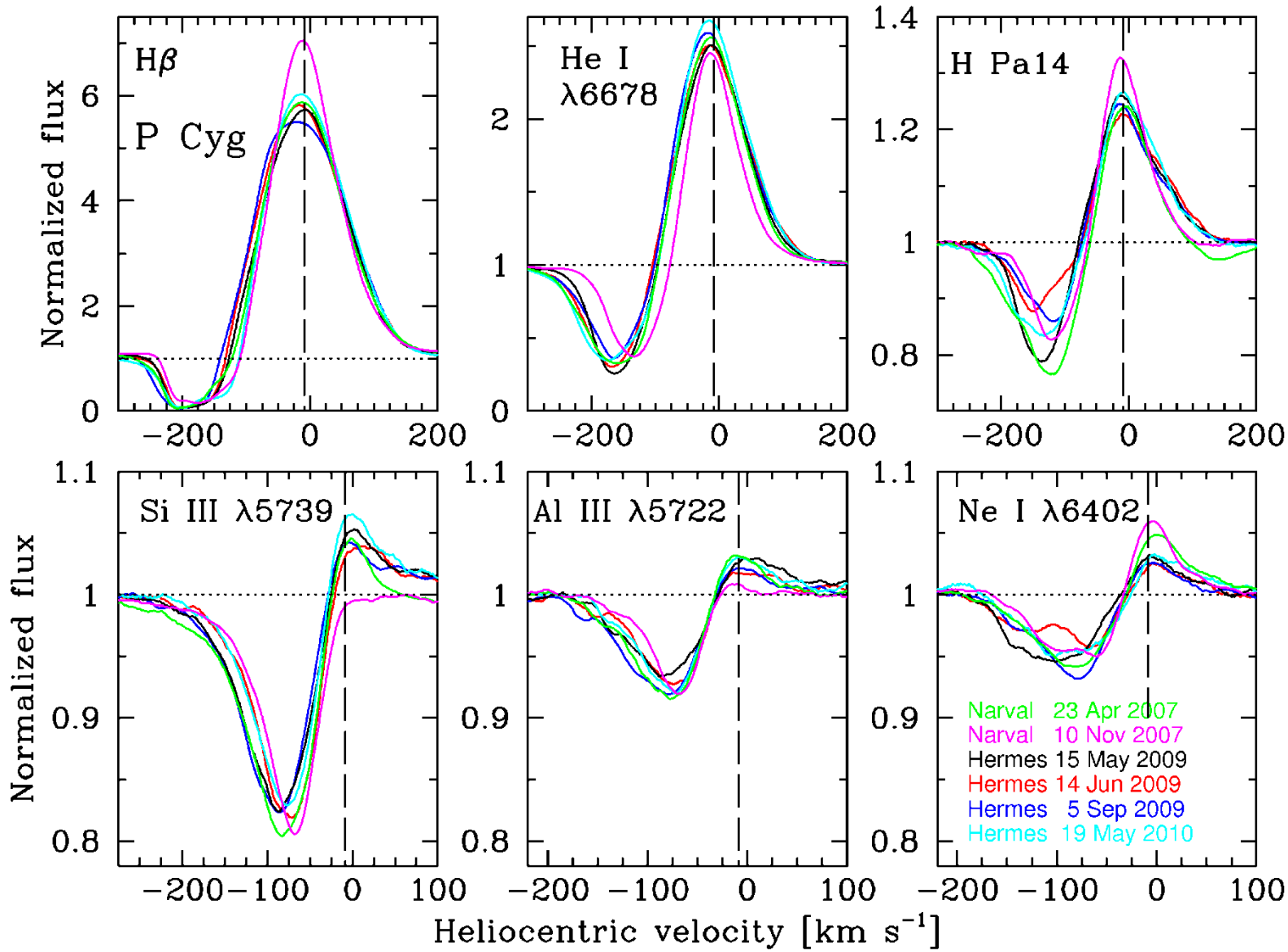
Formation of P Cyg wind line profile





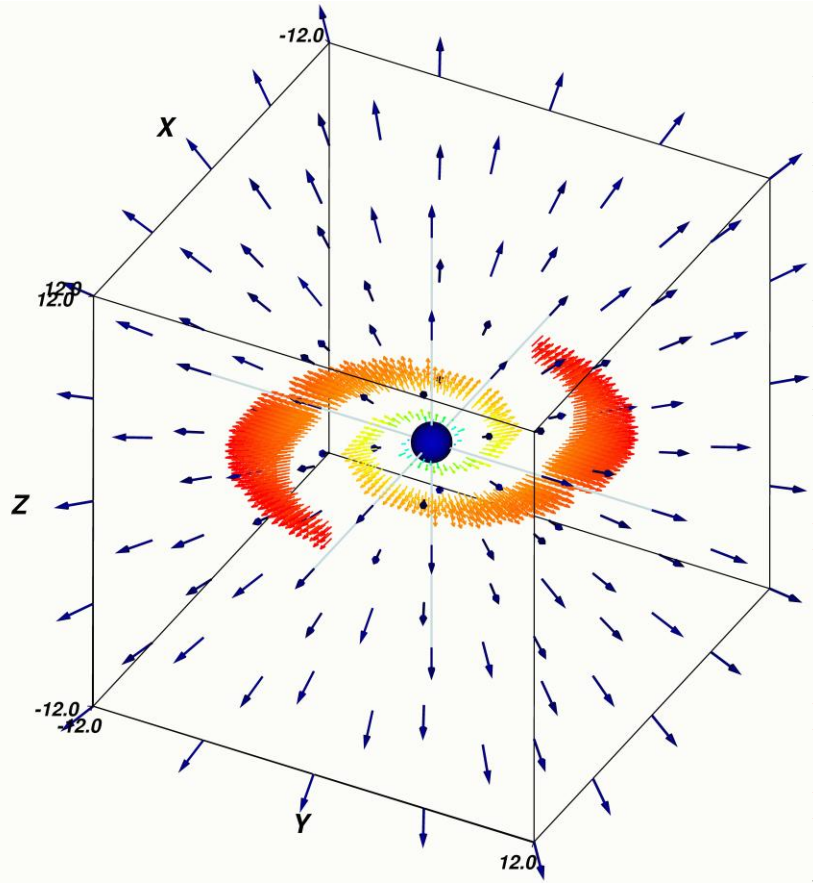
Absorption portion samples wind opacity in front of the stellar disc.

HERMES monitoring of wind lines in P Cygni



Variability of H & He line profiles due to changes in wind geometry or wind driving?

Development of 3-D radiation transport code Wind3D

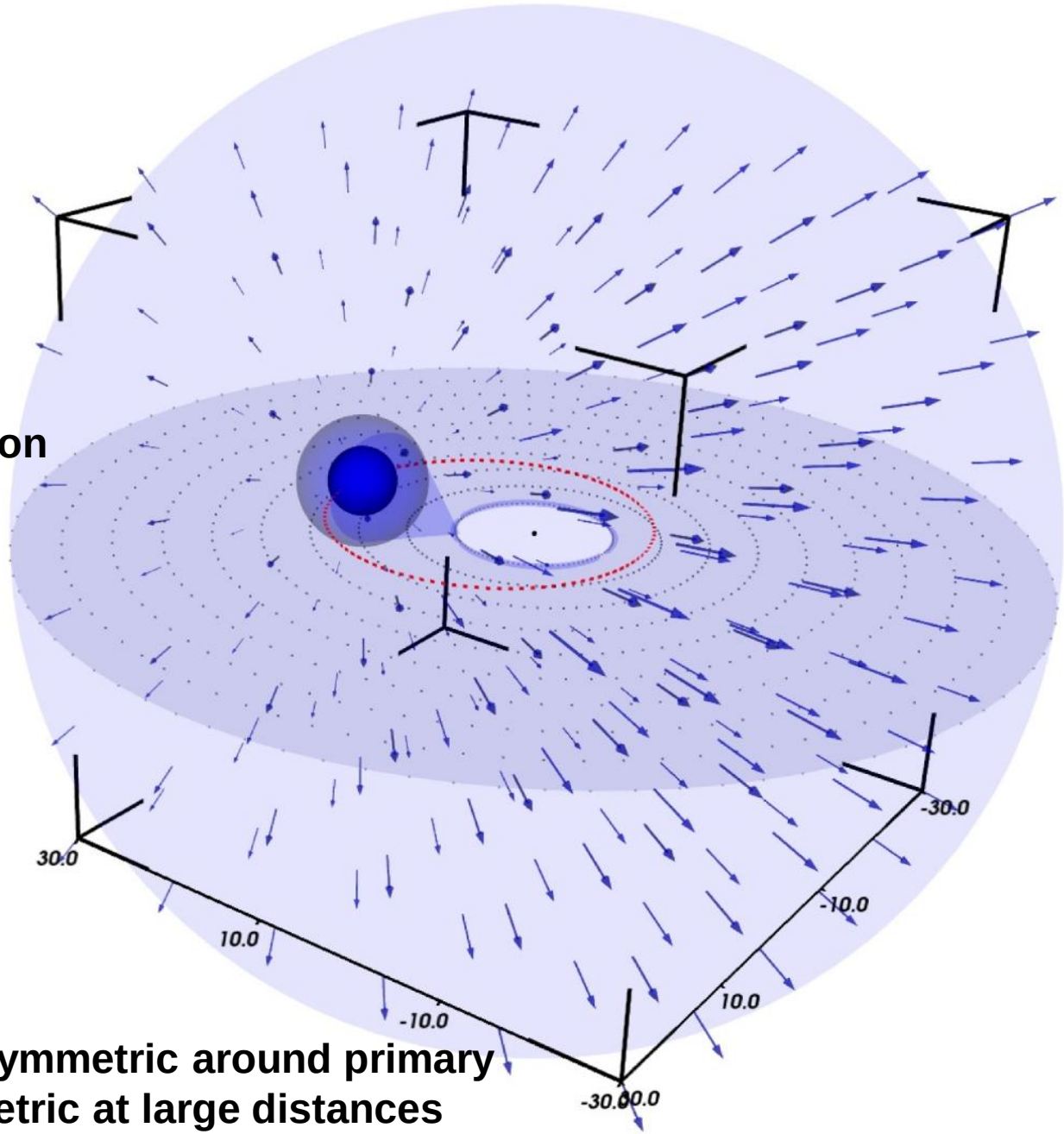


Hot star smooth wind with 'large scale' internal wind structures input for Wind3D

- implements Cartesian radiative transport scheme with short-characteristics method
- accepts arbitrary 3-D wind-density and -velocity structures
- exact lambda iteration of source function starting from Sobolev approximation in 3-D smooth wind model
- lambda iteration to non-Sobolev 3-D source function
- 100^3 source function points with 80^2 solid angles for 3-D intensity integral
- non-LTE radiative transfer equation is solved for 700^3 density and velocity points with 3-D source function interpolation technique
- two-level atom approx. for scattering dominated winds
- fully parallelized code with excellent load balancing
- 2008-2013: module implementation for parameterized structured wind input models based on CAK theory for radiatively-driven rotating winds. Combine with hydro modeling of rotational modulations using Zeus3D.

Asymmetric 3-D wind model of MWC 314

primary at apastron



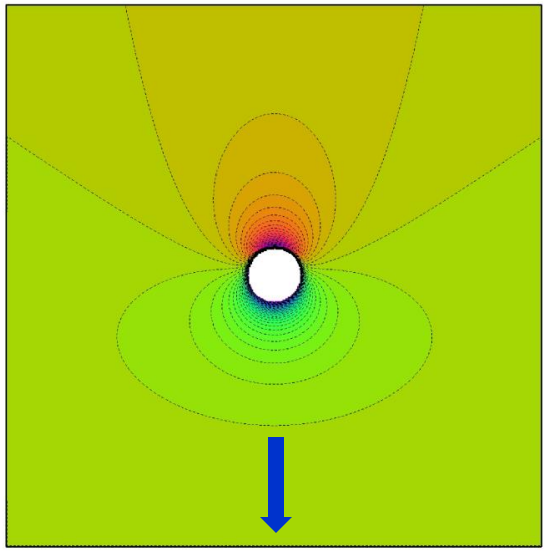
β-law wind model is asymmetric around primary and becomes symmetric at large distances

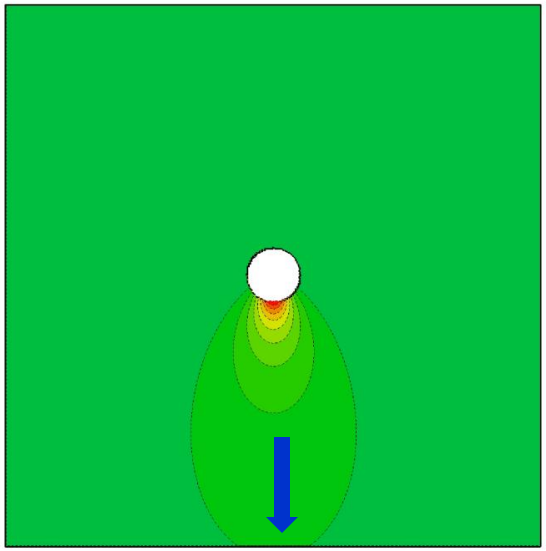
MWC 314 asymmetric expanding wind model

$v_{wind} - v_{sm}$

Equatorial wind velocity difference in observer frame

Modified β-law with same v_∞ around primary

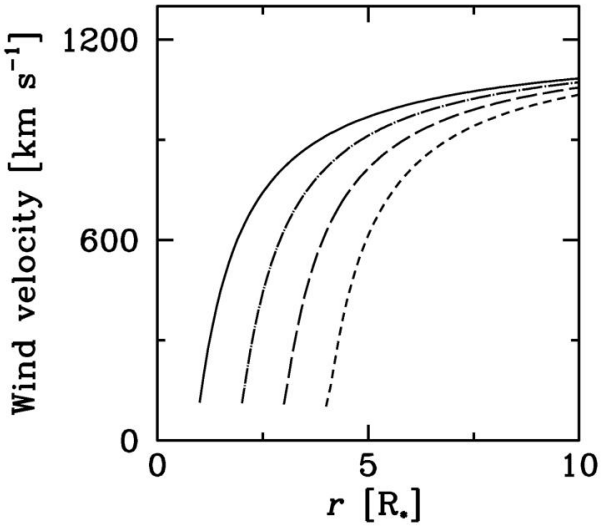


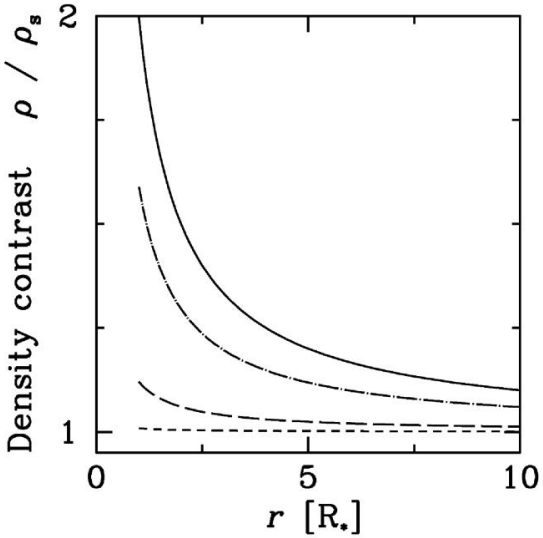


ρ / ρ_{sm}

opening angle = $\pi/4$

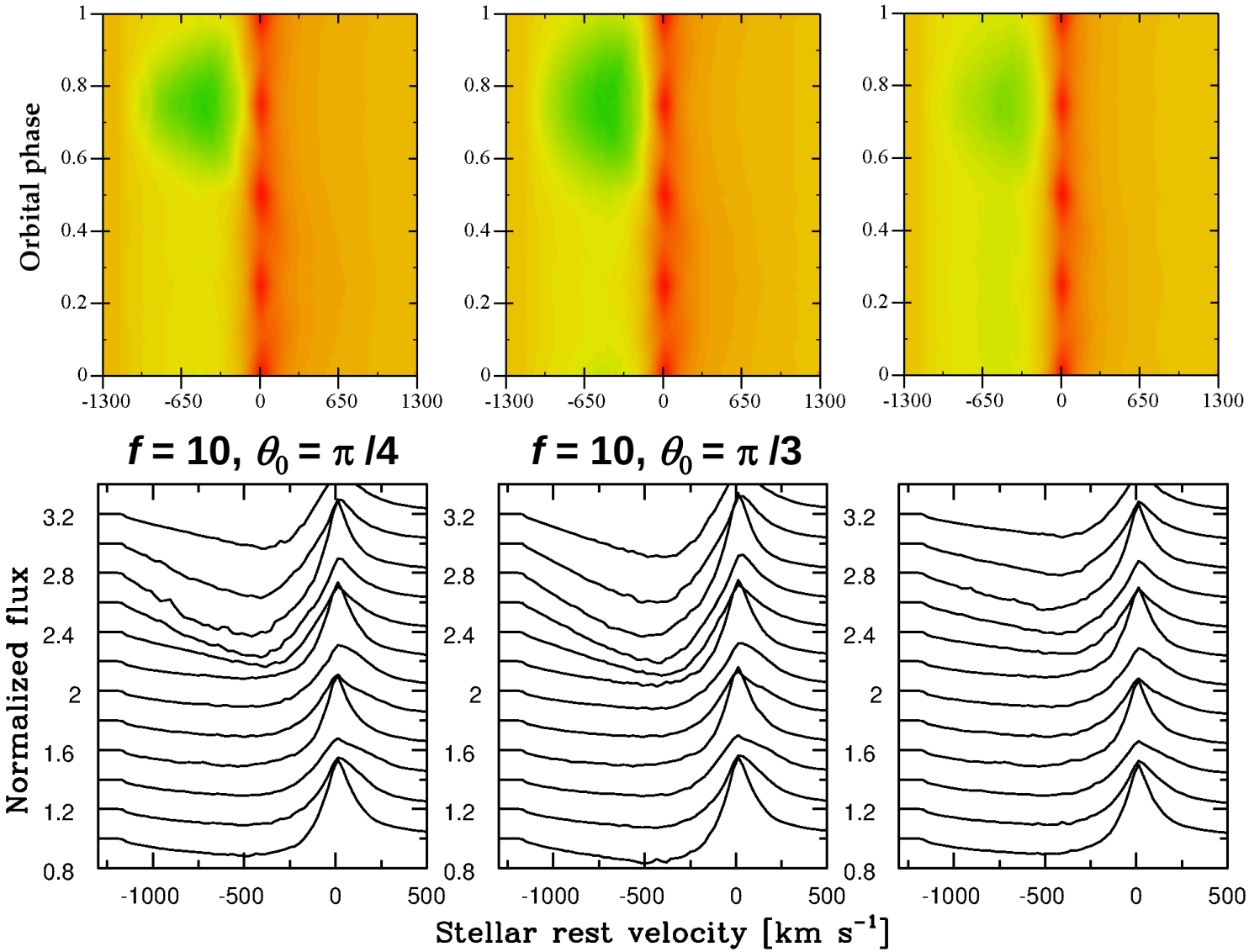
v_{wind}





- **Parametrized 3-D wind velocity & density model around primary star.**
- **Wind density enhancement of ρ / ρ_{sm}~3.3 in front of the primary's orbit.**

Wind3D RT fit to He I λ5876 orbital variability



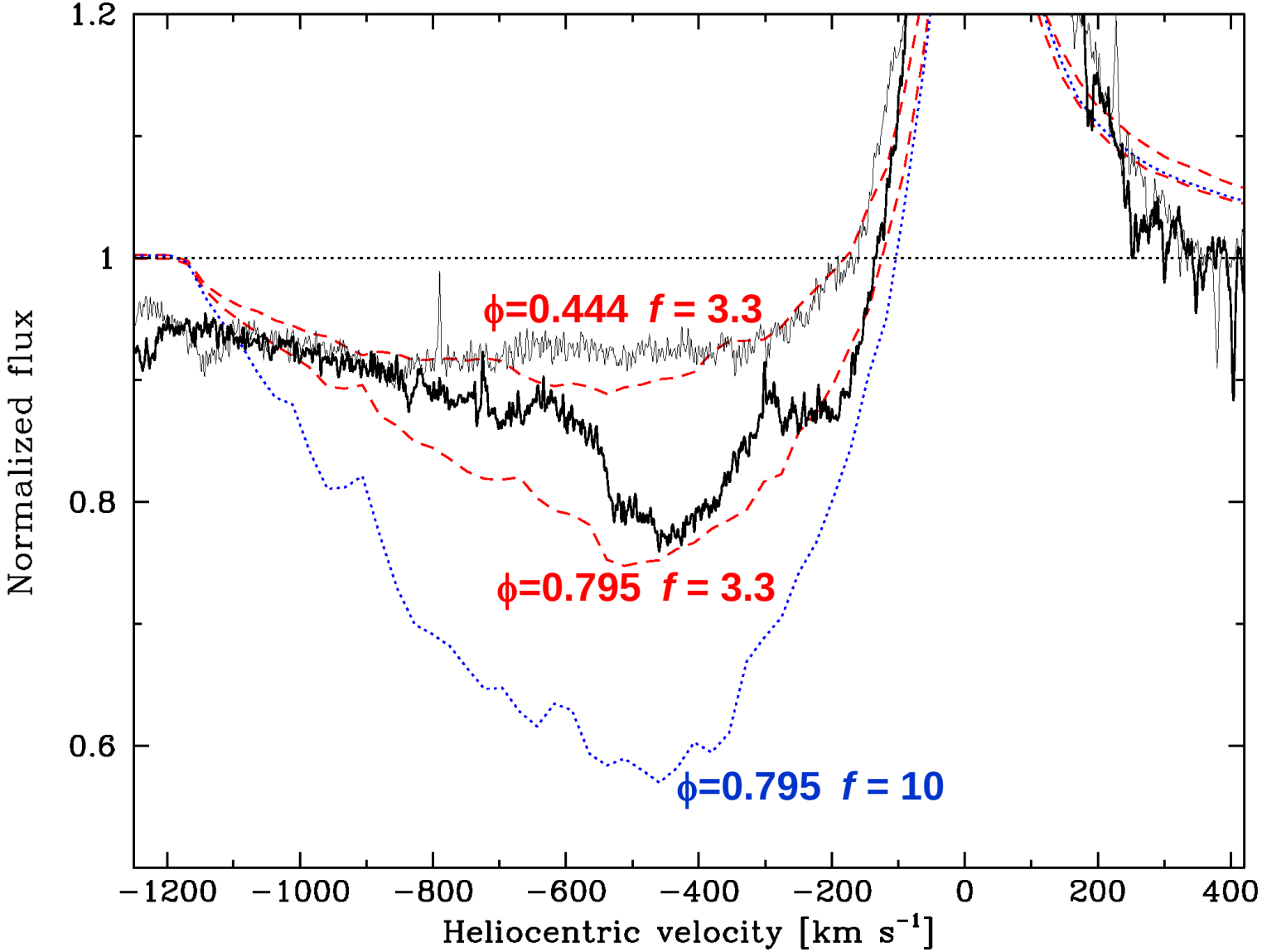
Best fit:
Wind density enhancement factor f = 3.3

opening angle $\theta_0 = \pi/4$

K_1 = 84.5 km/s (obs. Vrad)

- **Parametrized 3-D model reproduces enhanced absorption at ϕ=0.65 - 0.85.**
- **3-D RT Wind3D includes convergence of 3-D line source function with ϕ.**

Wind3D RT fit to He I λ5876 orbital variability



- **3-D best RT fit with Wind3D for wind density enhancement factor *f* = 3.3.**

Conclusions

- MWC 314 is a semi-detached massive binary system with $T\mathrm{eff}_1$ = 18 kK, M_1+M_2 > 65 $M_\odot$ and P_{orb} = 2 m.

- Accurate orbital elements: e=0.23, i = 73 13 , $a_1+a_2 \cong$1.22 AU.
  Accurate stellar parameters from combined RV- and V-curve:
  R_1 = 86.80 $R_\odot$ and R_2 = 20.41 $R_\odot$ ($T\mathrm{eff}_2$ = 6200 K).

- SED of MWC 314 identical to P Cygni, signaling a radiatively accelerating wind with r^{-2} smooth wind density structure.

- Optical emission lines and P Cyg line variability are orbitally modulated. He I P Cyg lines show wind outflow > 1200 km/s.

- We develop 3-D model of the asymmetric wind structure around the primary. Detailed fits to He I P Cyg absorption using Wind3D determine density increase of ~3.3 above smooth wind that leads the orbital path of the primary star. Wind collision region of primary with disc or a disc wind?