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

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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 ($P_{\text{orb}} \sim 1 \text{ m}$).

• 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 $P_{\text{orb}} = 60.8 \text{ d}$.

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

This work: $T_{\text{eff}} = 18000$ K, $\log g = 2.26$, $L^* / L_\odot = 5.8$, $\dot{M} = 3 \times 10^{-5} M_\odot / yr$

Very similar to true LBVs
Fig. 1. Narrow band Hα image of the environments of MWC314 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.
Fig. 1. Narrow band Hα image of the environments of MWC314 showing the large east-west bipolar feature 12.5 vertically. For all figures, north is up and east to the left.
• 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
Strong indication of binarity of MWC 314 from large RV shifts of \( \sim 33 \) 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:

\[ P_{\text{orb}} = 60.799 \text{ d} \]
\[ e = 0.235 \quad 0.003 \]
\[ i = 72.79 \quad 13.05 \text{ deg.} \]
\[ a = 262.58 \quad 19.52 \text{ R}_\odot \]
Photospheric absorption lines with orbital phase

Orbital phase

Normalized flux

Heliocentric velocity [km s^{-1}]
MWC 314 is massive binary system with primary filling its Roche volume.

V-curve shows partial eclipses for $i = 72.79 \pm 13.05$ deg.

**Primary star:**

$T_{\text{eff}}_1 = 18000$ K  
$M_1 = 39.66 \pm 4.3 \ M_\odot$  
$R_1 = 86.80 \ R_\odot$

**Secondary star:**

$T_{\text{eff}}_2 = 6200$ K  
$M_2 = 26.26 \pm 2.5 \ M_\odot$  
$R_2 = 20.41 \ R_\odot$
$R_1 = 86.8 \, R_\odot$

$a = 262.6 \, R_\odot$
Primary star fills its Roche lobe

- $\phi = 0.6$
- $\phi = 0.3$
- $\phi = 0.8$
- $\phi = 0.96$

**apastron**

**$V$ brightness maximum**

**periastron**
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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 4857 Å, showing outflow velocities above 1000 km s⁻¹.

Results. We find that MWC 314 is a massive semi-detached binary system of \( \approx 1.22 \) AU observed at an inclination angle of \( \approx 72.8° \) with an orbital period of 60.8 d and \( \varpi = 0.23 \). The primary star is a low-\( v_{\text{max}} \) 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.


1. Introduction

There is currently little known about the wind physics of the most luminous stars in the Galaxy by Miroshnichenko et al. (1998) with log(L*/L_☉)=6.1±0.3, \( T_{\text{eff}} \approx 20 \) to 30 kK, and \( M \sim 3 \times 10^{-3} \) 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 \( \approx 30 \) 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, the
Orbital modulation of optical emission lines

The graph shows the orbital modulation of optical emission lines with a focus on Ne I and Fe II. The data is presented in normalized flux versus heliocentric wavelength in Ångstroms. Two periods are highlighted: Oct 2010 and Jun 2009. The graph includes labels for different wavelengths and phase values.
Double-peaked metallic emission lines

B/R emission peak variability with $\phi$
Orbital variability of B/R emission maxima

Fe II B/R emission peak variability
B/R em. peak variability results from superposition with wind absorption formed around primary.
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.
He I P Cyg profiles in MWC 314 with $v_\infty > 1200$ km/s.

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

Also observed in the high H Balmer lines.
All He I lines show orbitally modulated wind absorption.

- Maximum wind absorption around $\phi = 0.65 - 0.85$, or max. RV blueshift.
Formation of P Cyg wind line profile

Absorption portion samples wind opacity in front of the stellar disc.
Variability of H & He line profiles due to changes in wind geometry or wind driving?
- 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.

Hot star smooth wind with ‘large scale’ internal wind structures input for Wind3D
Asymmetric 3-D wind model of MWC 314

β-law wind model is asymmetric around primary and becomes symmetric at large distances.
• Parametrized 3-D wind velocity & density model around primary star.
• Wind density enhancement of $\rho / \rho_{sm} \sim 3.3$ in front of the primary’s orbit.
Parametrized 3-D model reproduces enhanced absorption at $f = 0.65 - 0.85$.

3-D RT Wind3D includes convergence of 3-D line source function with $f$.

Best fit:
Wind density enhancement factor $f = 3.3$
opening angle $\theta_0 = \pi / 4$

$K_1 = 84.5$ km/s (obs. Vrad)
Wind3D RT fit to He I $\lambda$5876 orbital variability

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

![Graph showing normalized flux versus heliocentric velocity](image)
Conclusions

- MWC 314 is a semi-detached massive binary system with \( T_{\text{eff}1} = 18 \) kK, \( M_1 + M_2 > 65 \, M_\odot \) and \( P_{\text{orb}} = 2 \) m.

- Accurate orbital elements: \( e=0.23, \, i = 73 \pm 13 \), \( a_1 + a_2 \approx 1.22 \) AU. Accurate stellar parameters from combined RV- and \( V \)-curve: \( R_1 = 86.80 \, R_\odot \) and \( R_2 = 20.41 \, R_\odot \) (\( T_{\text{eff}2} = 6200 \) 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 \( \text{km/s} \).

- 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 \( \sim 3.3 \) above smooth wind that leads the orbital path of the primary star. Wind collision region of primary with disc or a disc wind?