Intrinsic polarization of Wolf Rayet stars,

hydrodynamic model and rotational effect

S. Abdellaoui, J. Krtička, P. Kurfürst

Masaryk University

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Motivation

- Wolf Rayet (WR) stars are thought to be the late evolutionary stage of some massive stars,
- Collapsar of fast rotating WR to black hole could generate a long gamma ray burst (Woosley 1993)
- Spectropolarimetry observation introcuded by Stevance et al. 2018,

WR groups

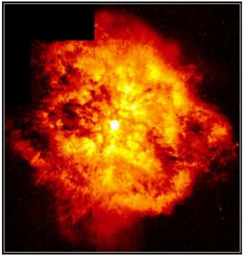


Figure: WR124 in the constellation Sagittarius is ejecting masses into interstellar medium (Credit: Yves et al, and NASA)

- Based on their emission line, WR stars are divided into three main spectroscopic groups (WN, WC, WO),
- WN stars show dominating nitrogen emission lines,

WR

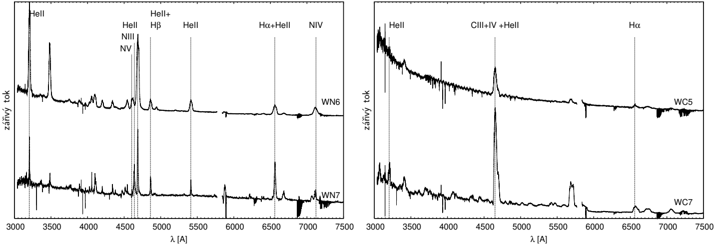


Figure: Intensity as a function of wavelength for WR spectra

- However WC stars are dominated by carbon and He emission lines with absence of H and N,
- WO stars are rare compare to WN, and WC, they have oxygen emission lines with some carbon emission lines,

HR diagram

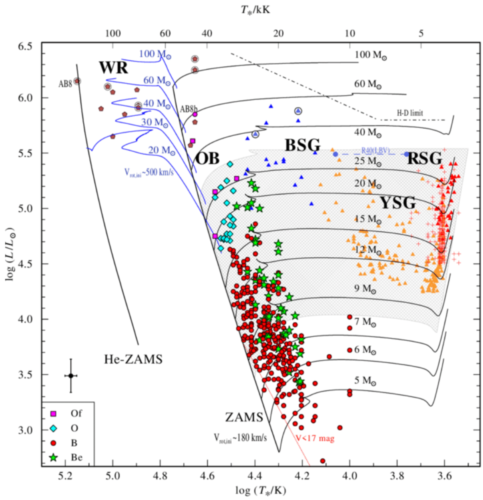


Figure: Hertzsprung-Russell diagram for massive stars(From Varsha et al. 2019)

Rotation effect

- Rapid rotation affects the structure and lives of many stars,
- The rotation could break the sphericity and lead to axisymmetric wind density (Owocki et al. 1996),
- If the electron scattering takes place in this axisymmetric envelope, the intrinsic polarization occurs,
- The polarization is perpendicular to the scattering plane,
- The scattering geometry is described in terms of the star's reference frame,
- And the angle of the scattering plane to the observer is considered in terms of (θ,ϕ) and the inclination (i).

Hydrodynamic

Solving hydrodynamic model equations in spherical coordinate system with oblate boundary conditions, using the VH1 code (Blondin 1990) coupled the radiative subroutine (Owocki et al 1994)

- Mass conservation equation $\partial_t \rho + \nabla(\rho.u) = 0$
- Momentum conservation $\rho(\partial_t u + (u.\nabla)u) = -\nabla P + \rho f^{ext}$
- Equation of state for isothermal wind $P = c_s^2 \rho$

where ρ is density, $u = (u_r, u_\theta, u_\phi)$ is the velocity in 3 direction, P is the gas pressure and f^{ext} is the external force.

In line-driven wind the external force is the sum of the effective gravity with line radiative force.

The line force is expressed as:

$$g_{lines}(\mathrm{r}) = \frac{k\sigma_{Th}^{1-\alpha}}{W^\delta \rho(\mathrm{r})^{\alpha-\delta} c v_{th}} \int_{\Omega_\star} (\mathrm{n}\nabla(\mathrm{n.v}))^\alpha \mathrm{n} I(\mathrm{n},\mathrm{r}) d\Omega$$

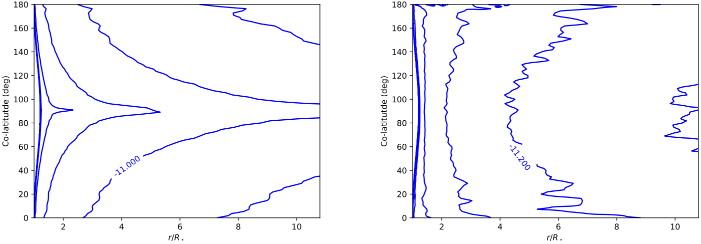
Stellar parameters

The mass of the two star is $7M_\odot$, and the terminal velocity is 5000km/s

WR	$\log(L/L_\odot)$	$T_\star$(kK)	$R_\star(R_\odot)$	$\log(\dot{M}/1M_\odot \mathrm{yr}^{-1})$
93b	5.30	160	0.58	-5
102	5.45	210	0.39	-4.92

- Base density is fixed proportional to $\dot{M}/c_s R_\star^2$ and subsonic outflow for the velocity at lower boundary, and outflow at upper boundary
- Reflective boundary in latitudinal direction
- Half sphere was considered for computational domain

Wind density contours



(a) Radial force only (b) +Gravity darkening

Figure: Log of density as a function of r and θ

- Radial force only leads to the formation of an equatorial disk (Wind Compressed Disk),
- Adding non radial forces and the gravity darkening the disk is suppressed and the matter leaves the star from the polar regions

Polarization computation

The polarization of electromagnetic radiation is described by Stokes vector S

$$S = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \tag{1}$$

I is the radiation intensity, Q and U describe the linear polarization, and V for circular polarization.
The degree of total and linear polarization, P and P_L can be expressed by Stokes's parameteres

$$P = \sqrt{Q^2 + U^2 + V^2}/I \tag{2}$$

$$P_L = \sqrt{Q^2 + U^2}/I \tag{3}$$

Polarization

- Because of the geometry is spherical $V = 0$, and $U = 0$ left two variables Q and I,
- we have to solve the radiative transfer equation in order to compute the radiation intensity $I$and as a result get P!!
- Call to Monte Carlo method is necessary,

Polarization

The intrinsic polarization is calculated according to the relation (Brown et al 1977, Cassinelli et al 1987):

$$P_R = \frac{3}{16}\sigma_T \sin^2 i \int_{R_\star}^{\infty}\int_{-1}^{1} n(r,\mu)(1-3\mu^2)D(r)\,dr\,d\mu.$$

Where n is the electron number density, $\mu = \cos(\theta)$, and $D = \sqrt{1-(\frac{R_\star}{r})^2}$ is the depolarization effect introduced by Cassinelli 1987

Brown et al 1977, showed that the polarization is positive if it is obtained from oblate geometry and negative if it is calculated from prolate structure.

Observation

Stevance et al 2018 derived the upper limit for the intrinsic polarization of the two stars and found that $P_R < 0.077\%$ ($V_{rot} < 324$km/s) for WR93b and $P_R < 0.057\%$ ($V_{rot} < 234$km/s) for WR102.

Due to limitation of the hydrodynamic we were not able to run for lower rotation velocities in order to compare with the observation.

Using the relation of Wood et al 1993, we got an estimate of the polarization for the two stars, where $P_{WR93b} \approx 8.6\%$ and $P_{WR102} \approx 18\%$.

$$P_0 = \frac{3\sigma_T}{32\pi} \frac{\dot{M}}{2\pi m_p R v_\infty},$$

Comparison

In order to check the hydrodynamic model we compared with an analytic approximation of wind compressed disk (WCD) model theory,

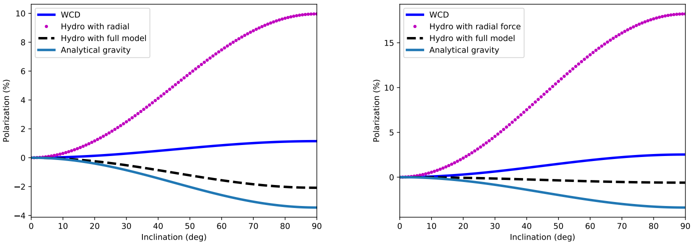
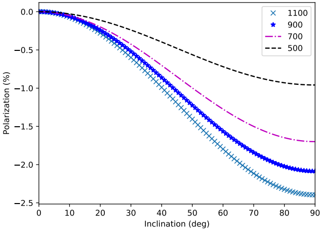


Figure: Comparison between analytical and hydrodynamic model of the polarization of WR93b and WR102, $V_{rot} = 900$ km/s

Full hydrodynamic model

To avoid the staircasing at the lower boundary conditions and to ensure the optically thin regime we integrated from $1.2R_{\star}$.



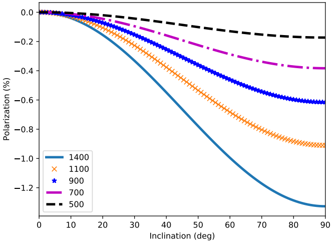


Figure: Polarization of WR93b and WR102 as function of inclination for different rotational velocities

Discussion

- The model with radial force only, oblate wind density distribution, gave a positive polarization,
- The model with non radial forces, prolate wind structure, leads to negative polarization,
- Increasing the rotational velocity will increase the polarization in absolute value,
- The polarization reaches its maximum when viewed edge-on

Angular momentum

WR	$P_R\%$	V_{rot} (Stevance's model)	V_{rot} (Current model)	$\log(j/1cm^2s^{-1})$
93b	0.077	324	277	17.88
102	0.057	234	444	17.85

- Threshold of angular momentum of collapsar is $\log(j/1cm^2s^{-1}) > 16$
- The obtained angular momentum exceed the threshold

Conslusion

The intrinsic polarization was obtained by integrating the density distribution for different rotational velocities.

- Radial force only leads to oblate density distribution as a result the polarization >0,
- Including non radial forces and gravity darkening leads to prolate density distrubition, the polarization becomes <0,
- The derived upper limit of angular momentum is comparable to the one from the observation,

Thank you for your attention