Accretion Simulations of η Car and the Parameters of the Binary System

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The IMPACT of BINARIES on STELLAR EVOLUTION

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η Car

- A very massive binary system: \( M_1 \approx 90 - 170 M_\odot \)
  \( M_2 \approx 30 - 80 M_\odot \)
- Luminosity: \( L \approx 5 \times 10^6 L_\odot \)
- Period: \( P \approx 5.54 \) yr
- Eccentricity: \( e \approx 0.85 - 0.9 \)
- Both stars blow winds that collide and form shocks.
- Spectroscopic event close to periastron passage.

η Car image of the Brγ line at velocity of −277 km/s
(VLTI-AMBER; Weigelt+ 2016)
The giant eruptions of η Car

- The primary is recovering from giant eruptions in the 19th century.
- Secondary may have played a role in triggering the eruption.

Smith & Frew 2010
The binary system η Car (today)

• Mass-loss rate of the primary:

\[
\dot{M}_1 = 2.5 \times 10^{-4} - 10^{-3} M_\odot \text{ yr}^{-1}
\]

(e.g., Smith+ 2003, Davidson & Hymphrey 2012, Groh 2012, Madura+ 2012).

• The secondary:
  – Less massive
  – Smaller mass loss
  – It is the main source for ionizing photons
  – \(T=37000-41000\text{K}\) (Verner+ 2005; Teodoro+ 2008; Mehner+ 2010).

Likely positions for η Car’s secondary star in the H-R diagram (Mehner et al. 2010)
The X-ray Cycle

X-rays are produced in a bow shock due to the collision of the dense wind of the primary with the lower density, higher velocity wind of the secondary.

Corcoran et al. 2015
The Event

Phase (0.01 ≈ 20 days)

The diagram shows the intensity of various emissions over the phase of an event, with markers for periastron and data points for Hel 10830, X rays, radio 7mm, and Hell 4686. The x-axis represents the phase, and the y-axis represents the arbitrary intensity. The data is from Damineli + 2008.
Variation in line intensities indicates that there is far less UV radiation during the spectroscopic event.

The $T \approx 40000K$ secondary is the main ionization source.

during the event the secondary radiation must be obscured from the surrounding gas.

The effective temperature of the obscured secondary decreases from $T_{\text{eff}} \approx 40000K$ to $T_{\text{eff}} < 25000K$ (Martin+ 2006).
The hot secondary accretes dense primary wind close to periastron passage.

It causes a reduction in the number of ionizing photons from the secondary.

Spectroscopic event

Lower excitation lines

X-ray minimum

Better match observations of the event.

More massive stars (rest of parameters unchanged)

• Higher accretion rate
• Longer accretion

(Soker 2003, 2005, 2007; Kashi & Soker 2009)
Our older analytic results

- Checked both Bondi-Hoyle and RLOF accretion rates
- Integration of accreted mass within the accretion radius over 70 days according to density distribution of primary wind.

Kashi & Soker 2009
Our older analytic results, cont.

- We obtained accreted mass
  \[ M_{\text{acc}} \approx 0.5 - 3 \times 10^6 M_\odot \]

- Angular momentum calculations suggested a thick disk is formed, obscuring secondary light from equatorial directions.
Older simulations

- Wind collision in a grid-based code.
- Secondary’s gravity not included.
- X-ray minimum was not obtained by the simulation.
- Accretion was not obtained.
- Not surprising - models with no accretion fail to reproduce the X-ray minimum.
Older simulations

- SPH simulations by Madura et al. (2013).
- The wind of the secondary curves around the wind of the primary.
- Colliding wind region remains
- No accretion.
A step forward

- Full 3D simulation by Akashi et al. (2013).
- Secondary gravity included, radiative cooling included.
- A filament of gas has reached the wind launching box around the secondary.

- Secondary gravity is essential for accretion to occur.
- Numerical viscosity is important.
Onset of Simulation (Kashi 2017)

- We use version 4.3 of the hydrodynamic code FLASH.
- 3D Cartesian grid: \((x, y, z) = \pm 8\) AU
- Our initial conditions are set 50 days before periastron.
- We place the secondary in the center of the grid and send the primary on a Keplerian orbit with eccentricity \(e = 0.9\).
- 5 levels of refinement with better resolution closer to the center (\(\approx 1.7\) R\(\odot\)).
- High resolution at the wind collision region – allows to follow hydrodynamic instabilities.
Physics included in the new simulations (Kashi 2017):

• Secondary gravity (important!).
• Self gravity (included but negligible).
• Radiative cooling (improved algorithm).
• Radiative transfer.
• Artificial viscosity (important for instabilities).
• Response of the secondary wind to accreted mass.
Accretion is obtained

Dense filaments of gas are accreted onto the secondary starting ~4 days before periastron passage.
Accretion (cont.)

- The filaments come from different directions.
- They are not formed by self-gravity but rather by hydrodynamic instabilities and thermal instability.
- Density range:
  \[ \rho = 10^{-12} - 10^{-11} \text{ g cm}^{-3} \]
- Filaments consequently break into clumps.
Destruction of wind collision region, followed by accretion onto the secondary.
Clumps Formation by the Plateau-Rayleigh Instability

smooth surface $\rightarrow$ filaments $\rightarrow$ clumps
Accretion Panoramic View

Kashi (2017)
Simulation results: accreted mass

Amit Kashi - Accretion Simulations of η Car
The effective temperature

- Accretion is mostly close to the equator.
- But in the meantime the secondary is spinning.
- Stellar rotation might average the values over latitude.
The effective temperature

- Accretion is mostly close to the equator.
- Therefore, the temperature around the equator drops more considerably.
- The poles of the secondary can continue to ionize the wind for longer time.
# Parameters of the Binary System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meaning</th>
<th>Conventional mass model</th>
<th>High mass model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>Orbital period</td>
<td>2023 days</td>
<td>2023 days</td>
</tr>
<tr>
<td>$e$</td>
<td>Eccentricity</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>$a$</td>
<td>Semi-major axis</td>
<td>16.64 AU</td>
<td>19.73 AU</td>
</tr>
<tr>
<td>$M_1$</td>
<td>Primary mass</td>
<td>120 M$_\odot$</td>
<td>170 M$_\odot$</td>
</tr>
<tr>
<td>$M_2$</td>
<td>Secondary mass</td>
<td>30 M$_\odot$</td>
<td>80 M$_\odot$</td>
</tr>
<tr>
<td>$R_1$</td>
<td>Primary radius</td>
<td>180 R$_\odot$</td>
<td>180 R$_\odot$</td>
</tr>
<tr>
<td>$R_2$</td>
<td>Secondary radius</td>
<td>20 R$_\odot$</td>
<td>20 R$_\odot$</td>
</tr>
<tr>
<td>$v_1$</td>
<td>Primary wind velocity</td>
<td>500 km s$^{-1}$</td>
<td>500 km s$^{-1}$</td>
</tr>
<tr>
<td>$v_2$</td>
<td>Secondary wind velocity</td>
<td>3000 km s$^{-1}$</td>
<td>3000 km s$^{-1}$</td>
</tr>
<tr>
<td>$\dot{M}_1$</td>
<td>Primary mass loss rate</td>
<td>$6 \times 10^{-4}$ M$_\odot$ yr$^{-1}$</td>
<td>$6 \times 10^{-4}$ M$_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>$\dot{M}_2$</td>
<td>Secondary mass loss rate</td>
<td>$10^{-5}$ M$_\odot$ yr$^{-1}$</td>
<td>$10^{-5}$ M$_\odot$ yr$^{-1}$</td>
</tr>
</tbody>
</table>
The High Mass Model

• Assumptions:
  – the two 19th century eruptions were triggered by periastron passages.
  – mass was lost
  – mass was transferred from primary to the secondary
  – the energy of the eruptions comes from gravitational energy of the accreted mass

• Result: High mass binary better matches the peaks of the eruption to occur during periastron passages.
High Mass model

- We take: $M_1 = 170 \, M_\odot$, $M_2 = 80 \, M_\odot$
- Same orbital eccentricity, same mass loss rates.
- Results:
  - Accretion starts earlier.
  - Accretion rate is higher.
  - Accretion lasts longer.
  - Secondary’s ionizing radiation is lower for longer duration.

Amit Kashi (2017)
Mass accreted onto the secondary

\[ M_{\text{acc}} \times 10^{-6} \, M_\odot \]

- conventional model
- high mass model

\[ t \, \text{(days)} \]

Amit Kashi - Accretion Simulations of \( \eta \) Car
Figure 5. Variation of the binary parameters (orbital period $P$, semimajor axis $a$, orbital separation $r$, eccentricity $e$, and specific angular momentum $h$) during the 20 year long GE of $\eta$ Car. The variations are given for different sets of parameters we use in the paper (see Table 1). Left: “Common model”; middle: “MTz” model; right: “MTe” model.
Line variations during the event are better explained with the high mass model.

Kashi & Soker (2016)
Simulations of a VMS recovering from a giant eruption

Kashi, Davidson & Humphreys 2015
Summary

• Accretion in η Car confirmed.
• Our simulations confirm that a ≃ few $x10^{-6}\ M_\odot$ are accreted onto the secondary during periastron passage.
• Our older analytic calculations of the accreted mass gave nice results.
• The accreted gas lowers the effective temperature from 37000-41000K to >25000K, mostly at low latitudes.
• It reduces the number of UV photons and explains the spectroscopic event.
• High mass model $M_1 = 170M_\odot$, $M_2 = 80M_\odot$ better agrees with observations.
• As accretion occurs now, it surely occurred during the giant eruptions!