Observational signatures of past mass-exchange episodes in massive binaries:
The cases of HD 149404 and HD 17505

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Definitions

- **Massive star**:  
  - $M > 10 \, M_{\text{Sun}}$, $T_{\text{eff}} > 20000 \, \text{K}$, $L > 10^6 \, L_{\text{Sun}}$  
  - $v_\infty \sim 2000 - 3000 \, \text{km/s}$ and $\dot{M} \sim 10^{-6} - 10^{-5} \, M_{\text{Sun}}/\text{year}$

- Large fraction of massive stars in **binary or higher multiplicity** systems

⇒ Orbital motion allows to observationally determine the masses of the stars
**Definitions**

- **Massive star**: 
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- Large fraction of massive stars in **binary or higher multiplicity** systems

⇒ Orbital motion allows to observationally determine the masses of the stars

But multiplicity can also lead to **complications**:

- **Interactions** between the stellar winds

- **Transfer** of matter and kinetic momentum through a **Roche Lobe overflow** interaction (Podsiadlowski et al. 1992; Wellstein et al. 2001; Hurley et al. 2002)

⇒ Binarity significantly affects the spectra and the subsequent evolution of the components
HD 149404

- Detached, non-eclipsing O-star binary, member of the Ara OB1 association

- Circular orbit with an orbital period of 9.81 days

- Orbital inclination of 21° (Rauw et al. 2001)

- Variability of emission lines (He II λ 4686, Hα) likely indicative of a wind-wind interaction (Rauw et al. 2001, Thaller et al. 2001, Nazé et al. 2002)

- One ON component due to significant nitrogen enrichment of the atmosphere
  ⇒ This could hint at a past binary interaction
HD 17505

- Multiple system composed of 7 visual companions, member of the Cas OB6 association
- Central object composed of three O-stars
- Low eccentricity orbit of the inner binary, $e = 0.095$, with an orbital period of 8.57 days
- Orbital period of the tertiary $< 61$ years
Previous determination of the orbital solution by Rauw et al. (2001)

→ Recover the individual spectra of both components via disentangling

(González & Levato 2006)
Spectral disentangling

Previous determination of the orbital solution by Rauw et al. (2001)

→ Recover the individual spectra of both components via disentangling

(González & Levato 2006)

This technique also has its limitations (González & Levato 2006)

- Broad spectral features are not recovered with the same accuracy as narrow ones
- Spectral disentangling does not yield the brightness ratio of the stars
- Small errors in the normalization of the input spectra lead to oscillations of the continuum in disentangled spectra
- Quality of the results depends on the RV ranges covered

In the specific case of HD149404: emission lines partly formed in the wind-wind interaction zone (Rauw et al. 2001, Thaller et al. 2001, Nazé et al. 2002)
**Spectral types and brightness ratio**

Based on the reconstructed individual line spectra:

- Conti’s quantitative classification criteria for O-type stars (Conti & Alschuler 1971, Conti & Frost 1977, Mathys 1988, see also van der Hucht 1996)

  ⇒ Primary star is an **O7.5 If** and secondary is an **ON9.7 I**

- \[ \frac{I_1}{I_2} = \left( \frac{EW_1}{EW_2} \right)_{obs} \left( \frac{EW_{O9.5}}{EW_{O7.5}} \right)_{mean} \]

  ⇒ Mean brightness ratio: **0.72 ± 0.17**

Good agreement with the ones derived by Rauw et al. (2001):

**O7.5I(f) + ON9.7I** and \[ \frac{I_1}{I_2} = 0.90 ± 0.16 \]
Rotational velocities and macroturbulence

- **Rotational velocities**
  - Determination of the $v \sin(i)$ of the stars of the system using a Fourier transform method (Gray 2008, Simón-Díaz & Herrero 2007)
  - Mean $v \sin(i) = 93$ and $63$ km$^{-1}$ for the P and S stars respectively

- **Macroturbulence**
  - MACTURB (Gray, R.O. 2010, [http://www.appstate.edu/~grayro/spectrum/spectrum276/node38.html](http://www.appstate.edu/~grayro/spectrum/spectrum276/node38.html))
  - $70$ and $80$ km$^{-1}$ for the P and S stars respectively
The CMFGEN code and method

Non-LTE model atmosphere code CMFGEN (Hillier & Miller 1998):

Equations of radiative transfer and statistical equilibrium in the co-moving frame for plane-parallel or spherical geometries

First approximation of gravity, stellar mass, radius and luminosity from literature (Martins et al. (2005), Rauw et al. (2001) and Muijres et al. (2012))
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**Iterative process** that permits us to adjust these parameters:

1. The temperatures: relative strength of the He I $\lambda$ 4471 and He II $\lambda$ 4542 lines (Martins 2011)
2. Surface gravities: through wings of Balmer lines
   Together with luminosities: iterative process through BC and $\frac{M_1}{M_2}$
3. Mass-loss rate and the clumping factor $\rightarrow$ Approximations
4. CNO abundances through the strengths of the associated lines
Results (1)

Figure 1: Part of the normalized spectra of the primary (top, shifted upwards by 0.5 continuum units) and secondary star (bottom), along with the best-fit CMFGEN model spectra (red).
Figure 2: IUE spectrum (black) and binary modelised spectra through re-combination of CMFGEN primary and secondary spectra (red).
Two very interesting results:

- **Overabundance in N** confirmed in the S star
  
  \[ \frac{[N/C]}{[C]} = 100 \frac{[N/C]}{[C]}_0 \]
  
  \[ \frac{[O/C]}{[C]} \geq 5 \frac{[O/C]}{[C]}_0 \]
  
  for the S star and
  
  \[ \frac{[N/C]}{[C]} \simeq 2 - 3 \frac{[N/C]}{[C]}_0 \]
  
  for the P star

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<tr>
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<th>Primary</th>
<th>Secondary</th>
<th>Sun 1</th>
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<tr>
<td>He/H</td>
<td>0.1</td>
<td>0.1</td>
<td>0.089</td>
</tr>
<tr>
<td>C/H</td>
<td>$1.02^{+0.10}_{-0.11} \times 10^{-4}$</td>
<td>$1.89^{+0.47}_{-0.47} \times 10^{-5}$</td>
<td>$2.69 \times 10^{-4}$</td>
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<tr>
<td>N/H</td>
<td>$1.32^{+0.20}_{-0.15} \times 10^{-4}$</td>
<td>$7.15^{+2.5}_{-1.8} \times 10^{-4}$</td>
<td>$6.76 \times 10^{-5}$</td>
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<tr>
<td>O/H</td>
<td>$7.33^{+1.1}_{-1.1} \times 10^{-4}$</td>
<td>$7.85^{+1.8}_{-1.1} \times 10^{-5}$</td>
<td>$4.90 \times 10^{-4}$</td>
</tr>
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1. (Asplund et al. 2009)
Results (3)

$M_P = 50.5\ M_{\odot}$ and $M_S = 31.9\ M_{\odot}$

Figure 3: Predictions of N/C vs. N/O as a function of stellar mass, on the left without any rotation of the stars and on the right including a rotation of $0.4 \times v_{\text{crit}}$ (Ekström et al. 2012).

Open square: primary star; Filled square: secondary star.
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  \frac{N}{C} = 100 \left[ \frac{N}{C} \right]_0 \\
  \frac{O}{C} \geq 5 \left[ \frac{O}{C} \right]_0 
  \]
  
  for the S star and
  
  \[
  \frac{N}{C} \approx 2 - 3 \left[ \frac{N}{C} \right]_0 
  \]
  
  for the P star

- **Asynchronous rotation**: \( P_P = 3.77 \) and \( P_S = 7.46 \) days
Two very interesting results:

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  \]

  for the P star

- **Asynchronous rotation**: \(P_P = 3.77\) and \(P_S = 7.46\) days

  ⇒ Tend to confirm mass and kinetic momentum transfer from the current S to the current P ([Vanbeveren 1982, 2011, Vanbeveren & de Loore 1994, Langer et al. 2003])
Figure 4: Parts of a normalized disentangled spectra of the primary (top, shifted upwards by 0.2 continuum units), secondary (middle) and tertiary star (bottom, shifted downwards by 0.3 continuum units) of HD 17505.
Figure 5: Parts of a normalized spectrum of the triple system HD 17505 (black), along with the current best-fit CMFGEN model spectra (red).
Conclusion

- HD 149404 is the first system in a sample of binary systems with past mass-exchange episode (Raucq et al. 2015, accepted)

  → First step to better understand the interactions in massive binaries

- Case of HD 17505: Difficulties inherent to the techniques to be further studied and overcome

- Other targets that are being studied: LSS 3074, HD 14633, HD 206267...
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Thank you
This study & Rauw et al. ([?])

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<tbody>
<tr>
<td>$R$ (R☉)</td>
<td>19.3 ± 2.2</td>
<td>25.9 ± 3.4</td>
<td>24.3 ± 0.7</td>
<td>28.1 ± 0.7</td>
</tr>
<tr>
<td>$M$ (M☉)</td>
<td>50.5 ± 20.1</td>
<td>31.9 ± 9.5</td>
<td>57.4 ± 14.3</td>
<td>36.5 ± 9.1</td>
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<tr>
<td>$T_{\text{eff}}$ (10⁴ K)</td>
<td>3.40 ± 0.15</td>
<td>2.80 ± 0.15</td>
<td>3.51 ± 0.1</td>
<td>3.05 ± 0.04</td>
</tr>
<tr>
<td>$\log \left( \frac{L}{L_\odot} \right)$</td>
<td>5.68 ± 0.06</td>
<td>5.63 ± 0.05</td>
<td>5.90 ± 0.08</td>
<td>5.78 ± 0.08</td>
</tr>
<tr>
<td>$\log g$ (cgs)</td>
<td>3.55 ± 0.15</td>
<td>3.05 ± 0.15</td>
<td></td>
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<tr>
<td>$\beta$</td>
<td>1.03 (f)</td>
<td>1.08 (f)</td>
<td></td>
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<tr>
<td>$v_\infty$ (km s⁻¹)</td>
<td>2450 (f)</td>
<td>2450 (f)</td>
<td></td>
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<tr>
<td>$\dot{M}$ (M☉ yr⁻¹)</td>
<td>$9.2 \times 10^{-7}$ (f)</td>
<td>$3.3 \times 10^{-7}$ (f)</td>
<td></td>
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<tr>
<td>BC</td>
<td>−3.17</td>
<td>−2.67</td>
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**Table 1:** The best-fit CMFGEN model parameters are compared with the parameters obtained by Rauw et al. (2001) for an orbital inclination of 21°. The effective temperatures from Rauw et al. (2001) were derived through the effective temperature calibration of Chlebowski & Garmany (1991) and permitted, along with the determined luminosities, to infer the stellar radii. The quoted errors correspond to 1σ uncertainties. The symbol “(f)” in the table correspond to values fixed from the literature (Howarth et al. 1997; Muijres et al. 2012).
Figure 6: Primary (open square) and secondary (filled square) stars in the HR diagram with evolutionary tracks for single stars at solar metallicity during the core H burning phase (Ekström et al. 2012), for non-rotating stars (left), and stars rotating at $0.4 \times v_{\text{crit}}$ (right). Dotted red lines: isochrones of 3.2 and 6.3 Myr for the left panel and of 4.0 and 8.0 Myr for the right panel.
Figure 7: Primary (open square) and secondary (filled square) stars in the log(g)-log(T_{\text{eff}}) with evolutionary tracks for single stars at solar metallicity during the core H burning phase (Ekström et al. 2012), for non-rotating stars (left), and stars rotating at 0.4 \times v_{\text{crit}} (right). Dotted red lines: isochrones of 3.2 and 6.3 Myr for the left panel and of 4.0 and 8.0 Myr for the right panel.