Stellar Winds & interferometry
Hot (massive) Stars

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Outline

• Physics of massive hot stars
• Application to active hot stars (NLTE physics)
• The SIMECA code
• Interferometry
• Results from Be stars, B[e] stars, HAe/Be
• Interacting binaries, Ups SgR, Eta Car
• Conclusions
Diagnostics of mass-loss

• Hot star winds can be observed through a variety of observations
  – UV resonance lines
  – Optical or IR emission lines
  – Continuum excess in IR or radio

• A theory of radiatively driven has been developed for hot stars which is broadly in agreement with observations.
Spectral lines from winds

- Spectral lines from winds can easily be distinguished from photospheric lines because of their large width or wavelength shift due to the outflowing motion of the gas in the wind.
- Wind lines can appear in absorption, emission or a combination of the two (P Cygni profile). For hot stars, two line formation processes tend to dominate.
Formation of Spectral lines

• **Line scattering** – If a photon emitted by the photosphere is absorbed by an atom, it causes an electron of the atom to be excited. Very quickly the photon is re-emitted by spontaneous emission. So it appears the photon was only scattered in another direction. If the line transition is from the ground state, the line is a resonance line and the scattering is called *resonance scattering*. Most P Cygni profiles are formed from resonance scattering.

• **Line emission by recombination** – If an ion in a stellar wind collides with an electron it can recombine. The most likely recombination is directly to the ground state, however it may recombine to an excited state. The resulting excited ion may then cascade downwards by photo-deexcitation. Each de-excitation results in the emission of a line photon. This process is responsible for H\(\alpha\) emission in hot stars.
P Cygni profiles

The most sensitive indicators of mass loss from hot stars are resonance lines from abundant ions, such as CIV 1550 Å in O stars, which generally have large oscillator strengths.

If the column density of the absorbing ions in the wind is relatively small, they can produce an absorption line that shows the Doppler shift (blue shifted since material is moving towards the observer).

If the column density of the absorbing ion is large, the blueshifted absorption is combined with emission that is symmetric about the line centre (from a halo of gas surrounding the stellar disk), producing a blue-shifted absorption component plus a red-shifted emission component.
Formation of P Cygni profile
Wind velocities of early-type stars are directly measured from so-called ‘black’ troughs of blue-shifted saturated P Cygni profiles – observed to range from several hundred to several thousand km/s.
Far-UV spectroscopy

Far-UV FUSE atlas of OB stars in Magellanic Clouds
Emission lines

Optical lines appear in emission for only very extreme winds – generally exclusively H\(\alpha\) at 6562Å may be used for OB supergiants.

Strength provides information on \(\frac{dM}{dt}\) since H\(\alpha\) is a recombination line (since proportional to \(\rho^2\))

Lines are narrower than UV resonance lines since H\(\alpha\) formed very close to star where density is high.

H\(\alpha\) fit to LMC O4If star – \(\frac{dM}{dt}=6, 8.5, 11\times10^{-6}\) Mo/yr
IR and radio excess

Stars with an ionized stellar wind emit an excess of continuum emission at long wavelengths, due to free-free `thermal’ emission from the wind with $f_\nu \propto \lambda^{-0.6}$ which falls off much slower than the photosphere ($f_\nu \propto \lambda^{-2}$). The $f$-$f$ emission depends on the density and temperature structure of the winds. If the wind velocity is known, the radio flux provides information on the mass-loss rates via

$$\frac{dM}{dt} \propto v_\infty f_\nu^{0.75} d^{1.5} \lambda^{-0.25}$$

This technique is limited to relatively nearby (few kpc) stars with strong winds due to poor radio sensitivity since the free-free emission is very weak.

*Mass loss rates of O supergiants are of order $10^{-6}$ Mo/yr (compare with $10^{-14}$ Mo/yr for Solar Wind), rather lower for O dwarfs.*
Excess emission from wind

Here we show the spectral energy distribution of a hot star with a \textit{strong} wind. The dashed line is that expected for a hydrostatic photosphere without a wind – the grey region is the IR and radio free-free excess from the wind. The excess is much weaker for most hot stars.
Radius \( (\tau \approx 2/3) \) increases with \( \lambda \)

Since the free-free opacity increases as \( \lambda^2 \), the optical depth along a line-of-sight into the hot star wind also increases with \( \lambda^2 \) as does the effective radius of the star, so the `radio photosphere' corresponds to \( \approx 10^2 \, R_* \).
What drives hot star winds?

- How are hot star winds driven? The dominant continuum opacity source in O stars is electron scattering. Does this drive the wind? If the force from electron scattering were to exceed gravity (known as the Eddington limit) the surface of a star could not remain bound and the star would blow itself apart.

- Instead, stellar winds are rather stable, using electrons bound in atoms to absorb the radiation: Radiation pressure is transferred to the wind material via spectral lines, which are plentiful in the UV. Bound e- provide much more opacity than free e- (e.g. opacity from CIV 1550 exceeds e.s. by $10^6$!)

- Hot stars, unlike the Solar Wind, have plenty of line opacity in the ultraviolet where most of the photospheric radiation is. This combination allows for efficient driving of winds in hot stars by radiation pressure.
Doppler shift

• The large radiation force on ions due to their spectral lines would not be efficient in driving a wind if it were not for the Doppler effect.

• In a static atmosphere with strong line-absorption, the radiation from the photosphere will be absorbed or scattered in the lower layers of the atmosphere. The outer layers will not receive direct radiation from the photosphere, so the radiative acceleration in the outer layers is strongly diminished.

• However, if the outer layers are moving outwards, there is a velocity gradient, allowing the atoms in the atmosphere to see the radiation from the photosphere as redshifted (it appears to be receding as viewed from gas in the expanding atmosphere). The Doppler shift allows the atoms to absorb undiminished continuum photons in their line transitions.
Line-driving

• Radiative acceleration due to spectral lines in the atmospheres of hot stars (main sequence OB stars, OBA supergiants, central stars of Planetary Nebulae, WDs) is very efficient for driving a stellar wind.

• This radiative acceleration in hot star winds is provided by the absorption and re-emission of UV photons in ions of abundant elements (CNO, Fe-peak) in the Lyman continuum ($\lambda<912\text{A}$).
Example

• The resonance line of NIV is at 765A, so an ion that absorbs such a photon will increase its velocity by $h\nu/mc = 37 \text{ cm/s}$. To accelerate a single N$^{3+}$ ion to 2000km/s requires $5 \times 10^6$ absorptions. In fact, since the wind is a plasma, the momentum gained by the N$^{3+}$ ion is shared with all constituents in the wind (via interactions with surrounding protons, ions, e-, due to the electric charge of the ion).

• Ions which provide the radiative acceleration constitute about only $10^{-5}$ of all ions by number (since H and He contribute negligibly to the acceleration since fully ionized) so if a typical ion increases its velocity by 20cm/s, the effective increase per absorption is $2 \times 10^{-3} \text{ cm/s}$. To accelerate the wind to 2000km/s requires $10^{11}$ absorptions!

• The terminal velocity is reached in a few stellar radii, so the time to accelerate the gas is $3R^*/v_\infty = 10^4 \text{s}$ if $R^* = 10R_{\text{sun}}$ so ions that provide the acceleration have to (and do!) absorb $10^7 \text{ ph/s}$ (typical of strong lines with large oscillator strengths).
CAK theory

The theory of radiatively driven winds was developed by Castor et al. (1975, CAK), with the radiative acceleration dependent on the fraction of optically thick lines (parameter $\alpha$), the number of strong lines (parameter $k$) and ionization ($\delta$). Using these parameters, it was found that

$$\frac{dM}{dt} \propto k^{1/(\alpha - \delta)}$$

and

$$v_\infty \propto \left(\frac{\alpha}{1 - \alpha}\right)v_{\text{escape}}$$

i.e. the mass-loss rate is predicted to scale with the number of strong lines, and the wind velocity is predicted to scale with escape velocity,

$$v_{\text{escape}} = \sqrt{2g_{\text{eff}}} R$$

where the effective gravity is the stellar gravity corrected for the reducing effect of radiative pressure via $\Gamma$ (related to $M$ and $R$)

$$g_{\text{eff}} = \frac{GM}{R^2} (1 - \Gamma)$$
The total radiative acceleration (and hence $\alpha$, $k$, $\delta$) can be calculated by summing the contributions of all possible lines for all elements. This is rather difficult, but was first carried out by Abbott (1982). There are wavelength regions where few lines contribute to the acceleration and others which are crowded with lines (e.g. $300<\lambda<600\text{Å}$ in O stars).

Typically $k>0.1$, $\alpha=0.65$, $\delta=0.1$ from summing all ions of all elements in O stars, predicting wind properties that are in reasonable agreement with observed wind properties. It has recently been found that CNO elements dictate the line driving in the outer wind (hence $v_\infty$) whilst Fe-peak elements control the inner wind (hence $\text{d}M/\text{d}t$).
Metallicity influence of winds

For O and early B stars

- $dM/dt \propto (Z/Z_0)^{0.85}$ *predicted* from radiatively driven wind. Observationally, stars in metal poor SMC galaxy do possess weaker winds than Galactic counterparts.

- $v_\infty \propto (Z/Z)^{0.1}$ predicted from theory, whilst observations show slower winds in SMC O dwarfs (thick lines) than Galactic stars (thin lines) from CIV 1550A & NV 1240A ultraviolet resonance lines.
Multiple scattering

The standard theory of line driving assumes that photons can be scattered only once in the wind which is a reasonable assumption for normal O stars. Line driving in WR stars is still controversial, since the strength of their winds appears to exceed the single scattering limit. The absorption by photons in different spectral lines is called *multiple scattering*. The process of multiple scattering is shown schematically here. Each scattering occurs in a different spectral line, successive scatterings occur at lower energy (longer wavelength).
Applications to active hot stars
Be stars and other friends
Open questions

• Origin of the Be phenomenon:
  – Why some hot stars are forming disks and some others not?
  – What is the effect of the rotation?
  – What is the effect of the magnetic field?
  – What is the influence of stellar winds?
  – What is the importance of these disks on the stellar evolution?
  – What is the impact on the ISM?
Active hot stars = NLTE physics
Non-LTE for hot stars

Radiation field is so intense in hot stars (O-type, OBA supergiants, WDs) that their populations are only weakly dependent on local \((T_e, Ne)\), consequently LTE represents a poor assumption.

Eddington limit: Radiation pressure equals gravity
Non-LTE in OB stars

• O and early B dwarfs possess intense radiation fields in which LTE is invalid. Hydrostatic equilibrium is invalid in OBA supergiants – their tenuous atmospheres lead to a drop in the line source function below Planckian value.

• In O stars, LTE profiles are much too small. Departures from LTE make He I and He II lines much stronger.

• For B stars, in the blue-violet spectra of B stars, some He I lines are formed in LTE, however red and IR lines are not collision dominated, instead photoionization-recombination processes dominate, so non-LTE is necessary.

• In A supergiants, reliable metal abundance determinations require non-LTE treatment – lines become stronger in non-LTE with corrections of up to factor of 10 for strong lines.
Hydrogen lines in $\beta$Ori (B8Ia)

LTE (dash) and non-LTE (solid) lines agree for Balmer lines (left), but LTE lines too weak for Paschen lines (below) in $\beta$ Ori
The SIMECA code
SIMulation Etoiles Chaudes Actives
(NLTE code)
SIMECA : Basic Scheme

**Input Parameters:**
- Hydro Code (CAK): $\rho, V_r, V_\phi, T$
- Statistical Equil. $n_1, n_2, n_7, n_e$ (LTE)
- $n_1, n_2, n_7, n_e$ (NLTE)

**Free Parameters**
- $m_1$: variation of the mass flux
- $m_2$: variation of the terminal velocity
- $C_1$: equatorial/polar mass flux ratio

**Envelop and Stellar Physical Parameters:**
- Temperature = $f(\theta)$
- Stellar Radius = $f(\theta)$
- Photospheric Density = $f(\theta)$
- Stellar rotational velocity
- Inclination
- Velocity at the photophere
- Equatorial terminal velocity
- Polar terminal velocity
- Polar Mass flux
- H/H+He

**Output Parameters:**
- SED
- Line Profiles
- Intensity Maps in Continuum
- Intensity maps in Lines
SIMECA : Basic Scheme

Based on hydrodynamical equations (CAK)
- Continuity Equation
- Mass flux conservation
- Perfect gas state equation

Hypothesis:
- Axial Symmetry (can be overcome)
- Stationarity
- Temperature independent of stellar latitude
- Velocities independent of stellar latitude
- Radiative Pressure due to line and continuum

We obtain in the envelope the following distributions:
- Density
- Velocity fields (expansion + rotation)
- Temperature (as a function of r)
We start with the LTE population levels (1 to 7 levels + continuum)

We solve the statistical population equations in the Sobolev approximation:

\[ n_i \left( \sum_{k=1}^{i-1} A_{ik} b_{ki} + B_{ik} \right) = \sum_{k=i+1}^{\infty} n_k A_{ki} b_{ik} + n_e^2 C_i(T_e) \]

\( A_{ik}, B_{ik}, C_i \): Absorption coefficients, spontaneous emission and recombination
\( \beta_{ik} \): Escape probability (function of the velocity gradient)

We calculate the level populations by iterations until we reach convergence in a 410x90x72 box.
SIMECA : Basic Scheme

Transfert Equation: \[
\frac{dI_\nu}{dz} = -\kappa_\nu I_\nu + \varepsilon_\nu
\]

We calculate \( \tau \) by integration: \( d\tau = -\kappa \cdot dz \) (along the line of sight)

In the continuum:
- Envelope Opacity: free-free emission and electronic diffusion
- Envelope Emission: free-free and free-bound emission

In the lines:
- Calculate \( \kappa \) et \( \varepsilon \) for the given transition
- Sobolev Approximation

Intensity as a function of spatial coordinates:
(in a plane perpendicular to the line of sight)
For a given transition (line) or as a function of the wavelength (continuum)
In a spectral line:
- Compute the iso-velocity regions \(\leftrightarrow\) Doppler Effect
  - Integrate these regions
    - Line Profiles
  - Integrate within a spectral bandwidth
    - Intensity maps

In the continuum:
- Spatial Integration
  - Spectral Energy Distribution (SED)
- Spectral Integration
  - Intensity maps in the continuum

Input Parameters:
- Hydro code (CAK): \(\rho, V_r, V_\phi, T\)
- Statistical Equil. \(n_1,\ldots,n_7,ne\) (LTE)
- \(n_1,\ldots,n_7,ne\) (NLTE)
- Radiative Transfer Continuum
- Radiative Transfer Lines
- Radiative Transfer Continuum

Output:
- SED
- Line Profiles
- Intensity Maps in Continuum
- Intensity maps in Lines
SIMECA: Basic Scheme

Input Parameters:
- Hydro code (CAK): $\rho, V_r, V_\phi, T$
- Statistical Equil. $n_1, ..., n_7, ne$ (LTE)
- $n_1, ..., n_7, ne$ (NLTE)

Radiative Transfer:
- Continuum
- Lines

Output:
- SED
- Line Profiles
- Intensity Maps in Continuum
- Intensity maps in Lines
Interferometry
Pb : How to obtain information on the brightness spatial distribution of an object?

=> Direct observation limited by the spatial resolution of the telescope

• Spatial resolution of a monolithic telescope:

  Image of a point source => Airy disk (R = 1.22\( \lambda \) / D)

  Resolution limit:
  Minimal angle to separate 2 points on the source (\( \approx 1.6\lambda / D \))

  \( \theta \) (mas) = \( 250 \lambda \) (micron) / D (m)

• In the visible:

  1.5” => D \( \approx 10 \) cm

  1.5 mas => D \( \approx 100 \) m (3 m on the Moon)

  0.005 mas => D \( \approx 30000 \) m (1 cm on the Moon)
Interferometry

Interferometry with 2 telescopes

Two telescopes with a diameter \( D \) separated by a baseline \( B \)

Similar to the Young’s fringes experiment:

Light interference from a single source

\[ \Rightarrow \text{Fringes in the Airy disk:} \]

\[ \text{Diameter} \quad d = 2.44 \frac{\lambda}{D} \]

\[ \text{Interfringe} \quad i = \frac{\lambda}{B} \]

Interferometer \( \Leftrightarrow \) Telescope with a diameter \( B \) + «mask with 2 holes with a diameter \( D \)»

\[ \Rightarrow \text{Spatial resolution equivalent to a monolitique telescope of diameter} \ B. \]

**Spatial resolution of an interferometer:**

\[ \theta (\text{mas}) = 250 \frac{\lambda (\text{micron})}{B (\text{m})} \]
Interferometry

Visibility Function

Visibility \((V) = \text{Fringes contrast} \) (between 0 and 1)

- Point source: \(V = 1\)  
  Fully resolved source: \(V=0\) (no more fringes !)

- Extended sources: Van-Cittert et Zernike theorem \(\Rightarrow V\) equal to the modulus of the object FT at \((u,v) = B/\lambda\)

**Exemple : two stars with different diameters.**

\(D_1 = 10\) mas et \(D_2 = 4\) mas

Limb darkned disk

Visibility as a function of baseline between 0 and 100 meters

1 m : \(V_1^2 = 1\) et \(V_2^2 = 1\) (object not resolved)

50 m : \(V_1^2 = 0\) et \(V_2^2 = 0.6\) (object 1 fully resolved)
The Very Large Telescope Interferometer

2 instruments available

- **MIDI**
  - 8-13μm
  - 2 telescopes
  - Modulus and Differential phase
  - $R=200$
  - $\theta_{min}=10\text{mas}$

- **AMBER**
  - 1.2-2.3μm (JHK)
  - 3 telescopes
  - Modulus, Differential phase, and phase closure
  - $R=35,1500,10000$
  - $\theta_{min}=2\text{mas}$
uv coverage after 8 hour observation with all UTs (object at -15°)

Resulting PSF is the Fourier transform of the visibilities at $\lambda = 2.2\mu m$ (K-band)
First fringes with the UTs (Oct 2001)

Fringes on Achernar (100-m baseline)
AT1 and AT2 with Open Domes

ESO PR Photo 07b/05 (14 March 2005)

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Spectro-interferometry
(Doppler Effect)

In the whole line

Geometry
Spectro-interferometry (Doppler Effect)

In the whole line

Geometry

Narrow spectral bandwidth within the line

Variation of the visibility modulus and phase as a function of wavelength

Geometry + Kinematics

Expansion/rotation, rotational law, inhomogeneities…
Be Stars: 
\(\alpha\) Arae
α Arae (VLTI/AMBER)

Intensity map computed with SIMECA (continuum @ 2 μm)
What is the rotation law within the circumstellar disk?

- Line profile and modulus of the visibility
- Differential phases
Keplerian ! ( Q. depuis 1866…)

\[ V_\theta \approx \frac{V_{rot}}{r^\beta} \]

Keplerian \( \beta = 0.5 \)
Angular Cons. Mt \( \beta = 1 \)

"First direct detection of a Keplerian rotating disk around the Be star \( \alpha \) Arae using the VLTI/AMBER instrument" Meilland, A., Stee, Ph. et al. 2006, A&A, astro-ph/0606404
And for a B[e] star?
B[e] star: CPD 57-2874: clearly an outflow!
An asymmetry detected in the disk of KCMa with the VLTI/AMBER.

Stellar wind and Be phenomenon

- Achernar

“The spinning Top Be star Achernar from VLTI/VINCI”


- Wind flux ≃ 5% of the stellar flux
- Elongation > 10 stellar radii
Is it possible to interpret Domiciano et al. data with another scenario?

Flattened star + Polar Jets ≈ Less flattened star + Small equatorial disk + Polar Jets
Disk and wind evolution of Achernar: the breaking of the fellowship

Kinematics

κ CMa

- No expansion ($V\Phi >> Vr$)
- non-Keplerian rotation ($\beta = 0.3 \pm 0.1$)
- Rotation sub-critical $V_{rot} \sim 0.52V_c$
- Inhomogeneity?

Achernar

- Critical rotation
- No disk during VINCI observations in 2002
- Disk between 1991 and 1998?

Meilland et al. 2006 A&A

Kervella et al. 2005 A&A

Vinicius et al. 2005 A&A
Disk Formation and Dissipation

Be Stars: One Ring to rule them all?


- Ring
- vs
- Mass-Flux variation

Study the variation of observables during the Disk dissipation

Visibilities:
- Amplitude and position
  - Of the visibility second lobe

Line profiles:
- Double-pics separation
  - Time of the dissipation

ESF Exploratory Workshop: Extreme Laboratory Astrophysics
**GROWING DISK TILL 2000 (PERIASTRON)**

- \( R_{\text{DISK}}(2003) \approx 10R_* \)
- \( V_r \approx 0.4 \text{km s}^{-1} \)
- **KEPLERIAN?**
- **MULTIPLE OUTBURSTS?**

Miroshnichenko et al. 2003 A&A 408,305
HAe/Be star: MWC 297

Interacting binaries: 
\( \beta \) Lyrae & Ups Sgr
Massive stars in interacting binaries

Massive interactive binary systems
- mass transfer and mass loss
- Complex circumstellar environment, rich in hot gas and dust

- system with exchange of mass ($M \sim 10-20 \, M_\odot$)
  - a donor star losing mass towards a star hidden in an accretion disc or a circumbinary structure ($\beta$ Lyrae et $\upsilon$ Sgr)
    - collaboration with the czech group of the Ondrejov observatory
**β Lyrae** (HD 174638, \( \delta = +33^\circ \), \( V = 3.4 \), \( d \approx 270 \) pc)

- System in 1\textsuperscript{er} phase of mass transfer
  - Variable composite spectrum
  - Moderate IR excess \( \Leftrightarrow \) no dusty environment
- Photometric and spectroscopic binary: \( P = 12.9 \) d, \( dP/dt = -19 \) s/y, \( i \approx 86^\circ \)
- 1994 International campaign

**Spectroscopy + photometry**

![Spectroscopy + photometry diagram]

**Spectro-Interferometry with GI2T**

Ground base N-S 51 m
\( \lambda = 654 - 677 \) nm \( R = 5000 \)

![Spectro-Interferometry diagram]

*calibrated visibilities*

<table>
<thead>
<tr>
<th>Spectral band</th>
<th>( \text{H}_\alpha )</th>
<th>( \text{He I} 6678 )</th>
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<tbody>
<tr>
<td>whole line</td>
<td>0.55 ( \pm ) 0.13</td>
<td>0.76 ( \pm ) 0.15</td>
</tr>
<tr>
<td>V peak</td>
<td>0.39 ( \pm ) 0.12</td>
<td>0.62 ( \pm ) 0.11</td>
</tr>
<tr>
<td>R peak</td>
<td>0.59 ( \pm ) 0.15</td>
<td>0.66 ( \pm ) 0.17</td>
</tr>
</tbody>
</table>

Whatever the orbital phase
- \( \sim \) E-W unresolved source in the continuum
- \( \sim \) N-S resolved source in the \( \text{H}_\alpha \) emission

- Jet Like structure in β Lyrae? (Harmanec et al., 1996)
A new vision of β Lyrae

- **Polarimetric observations:**
  - orbital axis $\theta \approx 160^\circ$ (Rudy, 1979)
  - UV line polarization $\theta \approx 162^\circ$ (Nordsieck et al., 1995)

- **radio observations:**
  - resolved source with MERLIN array at $\nu = 5$ Ghz ($\lambda = 6$ cm)
  - size $\sim 60 \times 47$ mas at $\theta \approx 157^\circ$ (Umana et al., 2000)

- **Light curves and UV spectrum modeling.**
  (Linnel et al., 1998)

- **3-D gas dynamical simulations of mass transfer.**
  (Bisikalo et al., 2000)

- **Disentangling of donor and accretion disc spectra.**
  No strong dependence of $H\alpha$ emission during the orbital cycle.
  (Ak et al., 2007)

**Mass transfer and mass loss study with CHARA**

- association of observations with high angular and spectroscopic resolution
- to solve the ambiguities of the interpretation of the spectro-photometric data
  - Visible (VEGA-CHARA) $\Rightarrow$ origin of the $H\alpha$ emission, resolution of the binary
  - Near IR (CHARA, AMBER-VLTI) $\Rightarrow$ free-free emission and $Br\gamma$ emission
β Lyrae observed with VEGA-CHARA?

<table>
<thead>
<tr>
<th>CHARA baselines</th>
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<tbody>
<tr>
<td>Base</td>
</tr>
<tr>
<td>S1-S2</td>
</tr>
<tr>
<td>E1-E2</td>
</tr>
<tr>
<td>W1-W2</td>
</tr>
</tbody>
</table>

+ VEGA

\[ \lambda = \text{[around H}_\alpha\text{]} \]

low resolution

(\(\lambda / \Delta \lambda = 1500\))

➢ a toy model for β Lyrae

At maximum elongation

Continuum

H\(\alpha\) emission

\[ F_{\text{donor}} = 0.62, F_{\text{disc}} = 0.38 \]
\[ F_{\text{bin}} = 0.18, F_{\text{jet}} = 0.82 \]

at \(\varphi_{\text{orb}} = 0.25 \text{ and } 0.75\), using aperture synthesis effect:

➢ the "donor-accretion" binary must be resolved with E1-E2 and W1-W2

➢ the H\(\alpha\) emission source must be resolved
Photocenter location depends of the central wavelength and of the flux ratio of the different emitting regions.

In H$\alpha$ line, observed light come from the bulk of the emission in addition to subjacent continuum.

The Interferometric Differential Imaging technique (Vakili et al., 1997) allows to measure the relative phase of the fringe visibility and to determine the relative position of the emitting regions.

➢ At $\lambda \approx 656$ nm, for the 107 m baseline, the fringe spacing is $i \approx 1.26$ mas.
➢ photocenter separation $\sim 0.4$ mas $\leftrightarrow \sim 110^\circ$ bump in the curve of the visibility phase across the spectral line.

➢ refine the location and extension of the H$\alpha$ emission?
Massive stars in interacting binaries

**Ups Sgr** (HD 181615, $\delta = -16^\circ$, $d \approx 500$ pc)
- brighter member of the type of extremely hydrogen-deficient binary stars (HdB stars)
- HdB are evolved binary systems in a second phase of mass transfer

- SB2, $P \approx 137.9$ d $dP/dt = -24$ s/y
- intense and variable H$\alpha$ emission
- strong IR excess $\Leftrightarrow$ very dusty circumbinary environment

- possible accretion disc and jet-like structure?  
  (Koubkay et al., 2006)
- **Spiral nebulae?**  
  (Narai, 1967)

**Mass transfer and mass loss study**
- association of observations with high angular and spectroscopic resolution
- to raise the ambiguities of the interpretation of the spectro-photometric data
  - extension of the circumbinary envelope (VLTI- MIDI & AMBER)
  - origin of the H$\alpha$ emission (VEGA on CHARA)
Eta Car (LBV)
The Luminous Blue Variable η Carinae and its Homunculus nebula: outburst in 1843 caused the Homunculus nebula.
• Extreme Luminous Blue Variable with spectacular outbursts
• Eta Carinae’s mass: 70 to 100 solar masses
• Dense aspherical stellar wind: diameter ~4 mas ~ 9 AU diameter
• High density of the stellar wind → star is not visible
• WR binary companion (P~5.5 yr), spectroscopic events …

• Observations: visibilities, differential & closure phases
• Resolution of η Car’s aspheric wind region: continuum, Br γ & He I; interpretation
• see Weigelt et al., A&A 464, 87 (2007)
VLTI-AMBER spectro-interferometry of η Car's stellar wind

HST image of the Homunculus nebula

η Carinae
continuum wind

Artist’s view
emission line wind

10 milli-arcsecond
The inner 1 arcsec: speckle objects, primary wind, binary, & wind-wind interaction zone

Hot companion (P~5.5 yr)

Primary

primary’s wind

strong UV radiation

weak UV radiation (secondary engulfed in primary’s dense wind)

Speckle objects: ejecta excited by Eta Car (bispectrum speckle interferometry, ESO 3.6 m, 2008)
η Car AMBER interferograms recorded with spectral resolution 12000 and the fringe tracker FINITO:

- 3 ATs, DIT 2 s, 2008
- Broad line: wind (~400 km/s)
- Narrow l.: speckle ejecta (50)
- Telluric lines
- Br γ 2.17: primary star wind
- He I: wind-wind interaction?
Car interferograms recorded with AMBER and the fringe tracker FINITO: Discussion of the broad & narrow lines

- 3 ATs, DIT 2 s
- Broad line: wind (~400 km/s)
- Narrow l.: speckle ejecta (50)

- FOV of AMBER observations:

ATs: 250 mas → narrow lines caused by the speckle objects

UTs: 80 mas → no narrow lines
In the continuum around the Br Gamma line, we found an asymmetry towards PA ~120° with a projected axis ratio of ~1.2. This result confirms the earlier finding of van Boekel et al. 2003 using VLTI/VINCI (K-band continuum).

These observations support theoretical studies which predict an enhanced mass loss in polar direction for massive stars rotating close to their critical rotation rate (Owocki et al. 1996, von Zeipel 1924).

These models predict a higher wind speed & density along the polar axis than in the equatorial plane.
Summary:

(1) Resolution of η Car's optically thick, aspheric wind region in the continuum & within Br γ & He I: Spectral resolution 1500 and 12000; fringe tracker observations with high SNR.

(2) 50% encircled-energy diameters (fit of Hillier et al. model CLV shapes):
  - K cont.: 4.3 mas
  - Br Gamma: 9.6 mas
  - He I 2.06: 6.5 mas (5 mas = 11 AU)

(3) K-band elongation: PA~120° & projected axis ratio of 1.2. This aspherical wind can be explained by models for winds from luminous hot stars rotating near their critical speed (e.g., Owocki et al. 1996). The models predict a higher wind speed and density along the polar axis than in the equatorial plane.

(4) We developed an aspherical stellar wind model which can explain the spectra, visibilities, differential & closure phases. Binary studies. Spectroscopic event.
Conclusions:

- Active hot stars: very nice laboratory to test NLTE physics
- Interferometry: powerful tool to study this physics with sub-mas spatial resolution.
- We need NLTE & 3D models to constrain the data
- Spectrally-resolved interferometry, i.e. with both spatial & spectral resolution is a key to constrain these models
- Multi-wavelengths studies are mandatory (physics = f(λ))
- Laboratory astrophysics can strongly help us since same processes can be studied in a « box », i.e. NLTE physics, radiative transfer, 3D hydro, coupling hydro-rad…and development of codes also useful for the astrophysical community…