Science with VEGA

Ph. Stee
Observatoire de la Côte d’Azur
& the VEGA Science Group
Science rationale for VEGA

- Early science (with 2 T):

  - The interacting binary β Lyrae (P =13 d), Hα, LR or MR, differential phase, June - October, baselines S1-S2, E1-E2, W1-W2, super-synthesis effect, simultaneous IR observations.

  - Disc formation around δ Sco, MR, long term observational campaign, March-May, short baselines (S1-S2, E1-E2), simultaneous IR observations.

  - Stellar activity and mass ejection of the supergiant RIGEL, MR & HR, Hα, Hβ, differential phase, October- November, S1-S2, E1-E2

  - Coronal magnetospheric or disc wind from the HAe/Be star AB Aur, LR, S1-S2 & E1-E2, super-synthesis effect

  - Measuring the disc dust and gas around the B[e] star HD 61623, LR & MR, Differential phase, S1-S2 & E1-E2, super-synthesis effect, simultaneous IR observations (Samer Kanaan’s thesis)
The interferometric Baade-Wesselink method

Important: study of systematics effects between Infrared and Visible ($\eta$, LD, p-factor)
Cepheids with the VEGA/CHARA instrument

1. Distances (LR - easy – short term): 32 Cepheids with VEGA/CHARA
   6 (B<100); 10 (100<B<220); 16 (B>220)

   ⇒ Precision of 0.01 mag. on the PL relation.

   ⇒ Exactitude: need of a study of the LD (average and variation) and p-factor ...

   Comparison V/IR

2. Dynamical structure of Cepheid atmosphere (HR, difficult):
   B=50->300;
   6 pulsations phases:
   ⇒ p-factor
   ⇒ Vrot.sini
   ⇒ Δη (distant Cepheids, LMC)

3. Hα line – circumstellar environment:
   HR (difficult)
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  - Line forming regions around WR stars, LR & MR
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  - Pop. II MIRA (extension of the program)
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  - β Cep, RR Lyrae and other pulsating stars: measuring the shell extension in lines and the shock waves propagation in the stellar atmosphere
A & B Supergiants: RIGEL

mv = 0.1, \( \phi = 2.77 \) mas:
S1-S2 (34m, \( v = 0.4 \))
E1-E2 (65m, \( v = 0.1 \), 1er visibility lobe max, tracking IR ?)

Kaufer et al. 1996
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- Early science (continue):
  - Measuring the optically thin atmosphere of pop. II MIRA: RT Cyg, LR, June - October, S1-S2, E1-E2, W1-W2, IR tracking & visible measurement.
  - Measuring the Limb-darkening and projection factor of pulsating Cepheides, ζ Gem, δ Cep, simultaneous IR observations (FLUOR).
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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 $\iff$ very dusty circumbinary environment

- possible accretion disc and jet-like structure?
(Koubisky et al., 2006)

**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)

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\[ H\alpha \]

\[ T_{\text{eff}} \sim 10500 \text{ K} \]
\[ M \sim 2.5 \text{ M}_\odot \]

\[ T_{\text{eff}} \sim 16000 \text{ K} \]
\[ M \sim 4 \text{ M}_\odot \]

IR excess?

~10 AU

\[ B_{\gamma}, H\alpha \text{ emission?} \]

H$\alpha$ absorption

\[ H\alpha \text{ absorption} \]

~B2-B5 Vpe

~A2 Ia shell

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Spiral nebulae?
(Narai, 1967)
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The Wind Structure of the O9.5Ia Supergiant α Cam

Why do we study the wind of massive stars?
• mass loss and stellar evolution
• momentum deposition and chemical enrichment of the ISM

Evidences of structured winds in O stars
• X-ray wind emission resulting from micro-shocks
• Discrete variable absorption features in wind lines
• UV wind line profiles cannot be matched by homogeneous wind models

Consequences of structured winds
• Lower mass loss rates by a factor of 3 to 10 at least
• Structures are formed deep in the wind
• Lower momentum deposition in the ISM (affect evolution of SN remnants)
• Effect on the predicted ionizing fluxes not assessed fully yet

Mass loss rates derived from homogeneous wind models need urgent revision. We need to constrain empirically the density structure of O star winds to build new realistic wind models of massive stars
The Wind Structure of the O9.5Ia Supergiant $\alpha$ Cam

**How** do we constrain the wind structure of O stars?
- mid-IR, sub-mm, and radio observations
- H$\alpha$ interferometry

**Density diagnostics**
- UV lines are sensitive to the wind density
- Recombination lines (H$\alpha$) are sensitive to the \textit{density-squared}
- Free-free continuum is sensitive to the \textit{density-squared}

**Mid-IR to radio observations**
- Free-free continuum probes further in the wind at longer wavelengths
- \textit{Spitzer} (GO cycle 3, PI: Lanz) IRS observations of the mid-IR continuum and hydrogen recombination lines of $\alpha$ Cam obtained in late 2006
- VLA radio fluxes existing in the litterature; sub-mm obs. in planing stage

**Proposed CHARA/VEGA campaign on $\alpha$ Cam**
- Wavelength-dependent visibilities in H$\alpha$ (also mapping through the wind)
- Several bases and orientations to look for non-spherical wind
- H$\alpha$ known to vary on several timescales: repeat the observations on daily, monthly, and yearly timescales to map changes in the wind (rotation, …)
- Photospheric radius: $\approx 30 \ R_{\odot}$; distance: $\approx 800 \ pc$; $V = 4.3$

\textbf{Wind extends from 0.15 to 0.4 mas}
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Science rationale for VEGA

- **Second phase (continue):**
  - Extragalactic targets: need AO, BLR characterization, larges baselines, LR
  - A Galaxy far, far away: other Galactic Cepheids
  - Target of Opportunity ([Novae](#), etc…)
RS Ophiuchi on day 13.8

D~1600pc
$\varphi_{\text{orb}} = 0.97$
Rrg~50 Rsol (M3III)
NB+disque~10 Rsol
Kcont: 2.2 mas (0.4mas/jour, 430km/s)
Brγ: 3.8 mas (0.69mas/jour, 720km/s)
HeI: 5.3mas (0.96mas/jour, 1000km/s)

325Rsol
2.5 mas
See you soon on the mountain!
Rapid rotators: differential rotation, flattening, gravity darkening

<table>
<thead>
<tr>
<th>Name</th>
<th>$V \sin i$ Km/s</th>
<th>Spectral Type</th>
<th>Mag V</th>
<th>Angular diameter</th>
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<td>A7V</td>
<td>0.77</td>
<td>~ 3 mas</td>
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<tr>
<td>Regulus</td>
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<td>B7V</td>
<td>1.35</td>
<td>~1.4 mas</td>
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<tr>
<td>zeta Ophiuchi</td>
<td>295</td>
<td>O9.5Ve</td>
<td>2.5</td>
<td>~0.5</td>
</tr>
</tbody>
</table>
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Fundamental parameters of stars with exoplanets: Diameter and Teff (cf Ellyn talk)

<table>
<thead>
<tr>
<th>star name</th>
<th>distance (pc)</th>
<th>V mag</th>
<th>K mag</th>
<th>_RAJ2000</th>
<th>_DEJ2000</th>
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<td>1.78</td>
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<td>5.79</td>
<td>3.27</td>
<td>12 05</td>
<td>15.10</td>
<td>1.13</td>
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<tr>
<td>Ups And</td>
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<td>5.00</td>
<td>3.50</td>
<td>13 28</td>
<td>25.85</td>
<td>0.85</td>
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<td>Tau Boo</td>
<td>15</td>
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<td>3.51</td>
<td>13 47</td>
<td>15.81</td>
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<tr>
<td>47 Uma</td>
<td>13.3</td>
<td>5.10</td>
<td>3.75</td>
<td>10 59</td>
<td>28.02</td>
<td>0.74</td>
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<td>HD 19994</td>
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<td>0.74</td>
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<td>5.40</td>
<td>3.86</td>
<td>16 01</td>
<td>02.65</td>
<td>0.73</td>
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<tr>
<td>55 Cnc</td>
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<td>4.00</td>
<td>00 39</td>
<td>21.87</td>
<td>0.71</td>
</tr>
</tbody>
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Massive stars in interacting binaries

**Massive stars**
- very hot and luminous
- main source for galactic UV flux
- impact on the interstellar medium and on the stellar formation process
- evolution affected by a strong stellar wind
- uncertain fundamental stellar parameters

**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 ($\beta$ Lyr et $\upsilon$ Sgr)

  collaboration with the czech group of the Ondrejov observatory
A new vision of $\beta$ 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 $\nu = 5 \text{ Ghz (} \lambda = 6 \text{ cm})$
  - size $\sim 60 \times 47 \text{ mas } \theta \approx 157^\circ$ (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 dependency of $\text{H}_\alpha$ 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 $\text{H}_\alpha$ emission, resolution of the binary
  - Near IR (CHARA, AMBER-VLTI) $\Rightarrow$ free-free emission and $\text{Br}_\gamma$ emission

\[ A = 58.5 R_\odot \leftrightarrow a \approx 1 \text{ mas} \]

Localization of the $\text{H}_\alpha$ and $\text{He I}$ emissions
\( \beta \) Lyrae observed with VEGA-CHARA

<table>
<thead>
<tr>
<th>CHARA baselines</th>
<th>Base</th>
<th>B (m)</th>
<th>Az(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-S2</td>
<td>34.0</td>
<td>170.3</td>
<td></td>
</tr>
<tr>
<td>E1-E2</td>
<td>65.9</td>
<td>56.6</td>
<td></td>
</tr>
<tr>
<td>W1-W2</td>
<td>107.9</td>
<td>99.1</td>
<td></td>
</tr>
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**VEGA**

\( \lambda = \text{[around H}\alpha\text{]} \)

low resolution

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

◮ a toy model for \( \beta \) 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 \( \varphi_{\text{orb}} = 0.25 \) and 0.75, using aperture synthesis effect:

◮ the "donor-accretion" binary can be resolved with E1-E2 and W1-W2

◮ the H\( \alpha \) emission source can be resolved
Photocenter location depends on the central wavelength and of the flux ratio of the different emitting regions.
- In the H\(\alpha\) line, observed light comes 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 \(~ 0.4\) 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?**
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δ Sco basic parameters

- One of the closest Be star d=123 pc
- One of the brightest V=2.2 K=2.7
- Spectral type: B0.2 IVe
- Well known non-eclipsing binary system with a 1.5 mag fainter companion with P=10.6 years and e=0.94
- Next periastron in 2011: interesting! (may trigger disk formation/destruction)
Disk Formation and Dissipation
Be Stars: One Ring to rule them all?
Meilland et al. 2006 A&A, 455, 953

Study the variation of observables during the Disk dissipation

- 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
- SED
Disk Formation and Dissipation

Achernar’s case

Vinicius, Zorec et al. (2005)

- Variation of the equivalent width (EW)
- Variation of the double-pics separation (DPS)
- $DPS_{\text{max}} = 460 \text{ km s}^{-1} \sim 2 \cdot \text{vsin} \ i$
- $DPS_{\text{min}} = 160 \text{ km s}^{-1}$
Disk Formation and Dissipation

A Correlation?

Intensity and DPS as a function of time

Diagram DPS/normalized Intensity
$\phi_M = \phi_{\text{max}}$ decrease as $t^{-0.5}$ and $v_r = 0.2 \text{ km.s}^{-1}$

Disk Formation and Dissipation

Achernar’s case

- Critical rotation
- Wind > 10R\ast
- Wind and disk « independants »
- Outburst between 1991-1995
  - V\textsubscript{r} \approx 0.2 \text{km s\textsuperscript{-1}}
  - R\textsubscript{max} \approx 8R\ast (if keplerian)
- 3\textsuperscript{d} Phase?
- New Outburst till 2002?
- AMBER LR (Imaging) + AMBER HR (kinematics)

Meilland et al. In preparation
disk formation and Dissipation

δ Sco

- Growing disk till 2000 (Periastron)
- $R_{\text{disk}}(2003) \approx 10R_*$
- $V_r \approx 0.4 \text{ kms}^{-1}$
- Keplerian ?
- Multiple outbursts?

Miroshnichenko et al. 2003 A&A 408,305
δ Sco simulations

Ring vs Disk Formation

Graphs showing the visibility of δ Sco simulations over different distances, indicating the comparison between ring and disk formation models.
δ Sco: visibility variation as a function of time

See: Anthony Meillard’s Thesis: Sept. 07
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