First science results with VEGA II: differential interferometry

by Ph. Stee

With the help of the VEGA TEAM and the following slides dealers:

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Fringes analysis

www.arkive.org
Differential analysis essentially done with the R2 grating (medium resolution)

<table>
<thead>
<tr>
<th>Grating</th>
<th>X-λ mode</th>
<th>Spectral distance between red and blue cameras</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: 1800tr/mm</td>
<td>R=35000 Δλ=6.7nm</td>
<td>18 nm</td>
</tr>
<tr>
<td>R2: 300tr/mm</td>
<td>R=5000 Δλ=40nm</td>
<td>140 nm</td>
</tr>
<tr>
<td>R3: 100tr/mm</td>
<td>R=1700 Δλ=120nm</td>
<td>Not usable simultaneously</td>
</tr>
</tbody>
</table>

Parameters of the red and blue cameras of the spectrograph

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Red camera</th>
<th>Blue camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{\text{min}} )</td>
<td>0.58( \mu \text{m} )</td>
<td>0.45( \mu \text{m} )</td>
</tr>
<tr>
<td>( \lambda_{\text{max}} )</td>
<td>0.87( \mu \text{m} )</td>
<td>0.75( \mu \text{m} )</td>
</tr>
<tr>
<td>( \lambda_{\text{ref}} )</td>
<td>0.7( \mu \text{m} )</td>
<td>0.57( \mu \text{m} )</td>
</tr>
<tr>
<td>Slit width</td>
<td>61( \mu \text{m} )</td>
<td>50( \mu \text{m} )</td>
</tr>
<tr>
<td>Maximum field of view (center of detector)</td>
<td>5.4”</td>
<td>4.2”</td>
</tr>
<tr>
<td>Number of spectral channels</td>
<td>173</td>
<td>156</td>
</tr>
<tr>
<td>Internal magnification of the spectrograph (between the slit and the image plane)</td>
<td>1.4</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Differential Spectral Analysis

- Estimation of the fringe visibility modulus $V(\lambda)$ and the differential phase $\Phi_{\text{diff}}(\lambda)$
- Data processing around Hα
  - Reference band: fixed, $\lambda_1 = 6560$ Å with $\Delta \lambda = 180$ Å
  - Science band: $\Delta \lambda = 4$ Å, moving by step of 4 Å, $\lambda_2 = 6572-6648$ Å
- Data processing in the continuum
  - Reference band: fixed, $\lambda_1 = 6560$ Å with $\Delta \lambda = 180$ Å
  - Science band: $\Delta \lambda = 4$ Å, moving by step of 4 Å, $\lambda_2 = 6572-6648$ Å
- For each step we measure $V(\lambda_1) \ast V(\lambda_2)$ and $\Phi_{\text{diff}}(\lambda_2)$ for science target and calibrator
- Calibration process is used to deduce $V_{\text{sci}}(\lambda)$
Data analysis of $\beta$ Lyr around H$\alpha$

**CAL : $\gamma$ Lyr 08h59**

$V(\lambda_1) \times V(\lambda_2)$

Contrast vs Wavelength (nm)

**CAL : $\gamma$ Lyr 09h39**

$\Phi_{\text{diff}}(\lambda_2)$

Phase (degree) vs Wavelength (nm)

**SCI : $\beta$ Lyr 09h20**

$V(\lambda)$

Intensity vs Wavelength (nm)

**Calibration of $\beta$ Lyr**

$\Phi_{\text{diff}}(\lambda)$

Phase (degree) vs Wavelength (nm)
Spectro-interferometry
(Doppler Effect)

In the whole line

Geometry
Spectro-interferometry

(Doppler Effect)

In the whole line

Narrow spectral bandwidth across the line

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

Geometry + Kinematics

Expansion/rotation, rotational law, inhomogeneities…

Spectral filter = spatial filter
Relation phase shift - sky displacement (close to H\(\alpha\))

\[
d(\text{mas}) = 0.37 \frac{\phi(\text{deg})}{B(m)}
\]

Ex: S1S2 B=34\(m\) \(\phi=20^\circ\) \(\Rightarrow\) \(d=0.21\) mas
W1W2 B=107\(m\) \(\phi=1^\circ\) \(\Rightarrow\) \(d=3.4\) \(\mu\text{as}\)!
Be stars: 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 geometry and kinematics of Be stars’s disks?
  – Are all Be stars binaries?
The CHARA/VEGA stars sample

- ψ Per    HD22192  B5Ve    d=214 pc
- 48 Per   HD25940  B3 Ve   d=169 pc
- χ Oph    HD148184 B1.5 Ve d=150 pc
- γ Cas    HD5394   B0 IVe  d=187 pc

- P-Cyg    HD193237 B2 pe  d=1923 pc
- β Lyr    HD174638 B7Ve  d=270 pc
- υ SgR    HD181615 F2p   d=513 pc
CHARA/VEGA baselines used

- \( \psi \) Per
- 48 Per
- \( \chi \) Oph
- \( \gamma \) Cas

Projected scaled Baseline

Major-axis from polarization
$\psi$ Per HD22

$S_1$  $S_2$

$W_1$  $W_2$

Projected scaled Baseline

Major-axis from polarization

214 pc

$\mu m V = 4.23$

$M = 4.1 M$

$V_{\text{sin} i} = 280 \text{ km/s}$

$i = 80^\circ$

$\epsilon = 0.35$ (mas)

km/s

35
ψ Per   HD22192  B5Ve  d=214 pc

S1S2 -03h21   S1S2 01h15
W1W2 -02h20   W1W2 00h35
HD2594

Projected scaled baseline

Major-axis from polarization
48 Per  HD25940  B3 Ve  d=169 pc

S1S2 01h59  S1S2 -03h17

W1W2 -03h36  W1W2 00h42
**γ Cas HD5394**  B0 IVe  d=187 pc

Preliminary conclusions

- $\psi$ Per: S1-S2 @ 2 A.H. Well resolved in H$\alpha$, clear S signature of a rotating disk (seen nearly edge-on), W1-W2 still need some work, blue data unusable.

- 48 Per: S1-S2 @ 2 A.H. Well resolved in H$\alpha$, S shape at 1 baseline but not for the 2 baseline, close in the sky plane (?), $35^\circ < i < 45^\circ$. Resolved with W1-W2 in H$\alpha$ but no S signature for the differential phase: disk + wind?

- $\chi$ Oph: S1-S2 @ 1 A.H. Resolved in H$\alpha$, small S signal in the line (compatible with $i=20^\circ$?)

- $\gamma$ Cas: S1-S2 @ 3 A.H. in natural and 2 polarized directions: S shape different in Natural and Polarized light: need to work on the interpretation ($i=45^\circ$).

- P-Cyg: S1-S2 @ 1 A.H. Well resolved in H$\alpha$, No signature of a rotating disk (wind!), W1-W2 still need some work…
Observations of interacting massive stars with CHARA/VEGA

Massive binary systems

- ν Sgr, binary system harboring an hydrogen deficient star (evolved system)
- β Lyrae: binary system with current mass-exchange

β Lyrae: D. Bonneau, O. Chesneau, D. Mourard, P. Stee
Interferometric observations of β Lyrae

1994
GI2T: 2T, $B = 51 \text{ m} +$ spectro-interferometry
$\lambda/\Delta \lambda \approx 5000 @ H\alpha, \lambda/B \approx 2.7 \text{ mas}$
- Resolved $H\alpha$ jet like structure
- Binary system unresolved
Harmanec et al., 1996

2005
NPOI: 3T recombination, $B = 19-53 \text{ m} +$ differential phases
$\lambda/\Delta \lambda \approx 36 @ H\alpha, \lambda/B_{\text{max}} \approx 2.6 \text{ mas}$
- Images of the $H\alpha$ emitting region
Schmitt et al., 2009

2007
CHARA/MIRC: 4T recombination, $B = 34-331 \text{ m}$
Interferometric imaging in H band, $\lambda/B_{\text{max}} \approx 1.0 \text{ mas}$
- Eclipsing binary resolved
Zhao et al., 2008

2008 ...
VEGA-CHARA, 2T (3T), $B = 34-331 \text{ m}$
Spectro-interferometry + differential phase imaging
$\lambda/\Delta \lambda \approx 5000 @ H\alpha, \lambda/B_{\text{max}} \approx 0.4 \text{ mas}$
- Shape and size of the $H\alpha$ emitting region?
- Morphology of the binary system?
CHARA/VEGA observations of β Lyrae

2008/07/30
TU 04h48 \( \varphi_{\text{orb}} = 0.496 \) B=34.1 m

2008/08/03
TU 04h51 \( \varphi_{\text{orb}} = 0.805 \) B=34.0 m

2008/08/05
TU 06h55 \( \varphi_{\text{orb}} = 0.966 \) B=34.0 m
TU 09h20 \( \varphi_{\text{orb}} = 0.974 \) B=32.5 m

2008/08/08
TU 07h15 \( \varphi_{\text{orb}} = 0.199 \) B=33.9 m
TU 07h54 \( \varphi_{\text{orb}} = 0.201 \) B=34.0 m
Differential Spectral analysis of β Lyrae observations

Modulus and Phase of the visibility around Hα

2008/07/30

• $V_{\text{obs}} \approx 0.65$
• $c_{\text{cont}} \approx 0.36 \Rightarrow V_{\text{jet}} (H\alpha) \approx 0.45$
• $\Phi_{\text{diff}} \approx -9^\circ$
• $\sigma_\Phi (\text{cont}) = 1.4^\circ$

2008/08/03

• $V_{\text{obs}} \approx 0.75$
• $c_{\text{cont}} \approx 0.40 \Rightarrow V_{\text{jet}} (H\alpha) \approx 0.58$
• $\Phi_{\text{diff}} \approx +15^\circ$
• $\sigma_\Phi (\text{cont}) = 4.5^\circ$

2008/08/05

• $V_{\text{obs}} \approx 0.67$
• $c_{\text{cont}} \approx 0.30 \Rightarrow V_{\text{jet}} (H\alpha) \approx 0.53$
• $\Phi_{\text{diff}} \approx -11^\circ$ and $\Phi_{\text{diff}} \approx +32^\circ$
• $\sigma_\Phi (\text{cont}) = 3.2^\circ$

2008/08/08

• $V_{\text{obs}} \approx 0.73$
• $c_{\text{cont}} \approx 0.36 \Rightarrow V_{\text{jet}} (H\alpha) \approx 0.52$
• $\Phi_{\text{diff}} \approx +8^\circ$
• $\sigma_\Phi (\text{cont}) = 1.4^\circ$
Observations β Lyrae with CHARA/VEGA

Preliminary results

- the source is unresolved in the spectral continuum.
- the source associated with the Hα emission is clearly resolved.
  the value of the visibility is nearly constant with the orbital phase.
- the differential phase exhibits significant offset in the Hα line.
  offset is correlated with the orbital phase.

Next step

- to precise the present analysis of the Hα and HeI observations.
- observations with longer baseline to resolve the binary system.
- interpretation of the results using a morphological model of β Lyrae.
**Ups Sgr** (HD 181615, δ = -16°, magV = 4.6)
- the brightest of the Hydrogen deficient stars (HdB stars)
- mass transfer stage.
  - SB2, P ≈ 137.9 j dP/dt = -24 s/an
  - Intense and variable Hα emission
  - Strong IR excess! ⇔ large and big dusty envelope

**Characteristics of the system from spectroscopic monitoring**

Orbital radius: \( a \sin i = 207.4 R_\odot = 0.965 \) UA
\( d = 595 \) pc (HIP, van Leeuwen 2007) \( \Rightarrow a'' \sin i \approx 1.6 \) mas
(Koubsky et al. 2006)

**Stellar discs** (Dudley et Jeffery, 1990)
\( R_1 \approx 60 R_\odot, \Phi_1 \approx 0.9 \) mas and \( R_2 \approx 4 R_\odot, \Phi_2 \approx 0.06 \) mas

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**Interferometric observations**

- mid-IR, VLTI-MIDII
- near-IR, VLTI-AMBER, CHARA-MIRC
- Visible, CHARA-VEGA
The dusty disk of υ Sgr constrained by MIDI/VLTI observations

- geometry of the circumbinary dusty envelope
- constraints on the orbital parameters

Inclination $i \sim 50^\circ$, P.A. of major axis $\Omega \sim 80^\circ$
Total mass of the system $> 15 \, M_\odot$

Netolicky, Bonneau, Chesneau, Kousky et al. 2009
Promising CHARA/VEGA observations of Ups Sgr

**VEGA configuration**
- mid-spectral resolution $R = 5000$
- Blue channel ($\lambda \sim 500$ nm)
- Red channel ($\lambda \sim 650$ nm including Hα)

**Results**
- **S1S2 baseline** ($B_{\text{sky}} = 23$ m, PA = -16°):
  - In the continuum, $V^2 \sim 0.7$
  - In Hα, dip of the visibility, phase offset of ~ 30°
- **W1W2 baseline** ($B_{\text{sky}} = 107$ m, PA = 97°):
  - In the continuum, $V^2 \sim 0.6$
  - In Hα, $V^2 < 0.1$

**Preliminary conclusions**
- High continuum visibility in both baseline
- over-resolved source + compact source
  - Compact source probably dominated by the primary flux.
  - Extended source due to the scattered light from the dusty disk.
- Extended source in Hα  FWHM ~2.5mas
  - i.e. surrounding the 2 stellar components.
- Position of the Hα photocenter $\neq$ of the continuum source
Future directions

- Clearly a vibration problem on W1W2 with W2 as a reference
- Very easy to obtain good fringes with S1S2
- To obtain usable data with the blue camera we need good seeing conditions (correlation SNR vs r0 to be done).
- Difficult to find (good) calibrators especially for the large baselines.
- At least 3-4 papers to come for 2009....
Thank you !
χ Oph    HD148184 B1.5 Ve    d=150 pc

Projected scaled Baseline

Major-axis from polarization

Φ(mas)=0.38
χ Oph  HD148184 B1.5 Ve  d=150 pc
\( \gamma \) Cas HD5

7 pc

S1S2 00h51

- Projected scale
- Major-axis from

\( \kappa = 10 \, \kappa_\odot \)

- Vsini = 230 km/s
- i = 45°
- \( \Phi \) (mas) = 0.45