Stellar Interferometry with Air Cherenkov Telescope Arrays

- Atmospheric Cherenkov Telescopes (ACT)
- Michelson Interferometry
- Intensity interferometry
- A modern Intensity Interferometer with ACT
- Capabilities

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Thursday September 13th, HTRA, Edinburgh 5th 2006
Air Cherenkov Telescopes

1 TeV
\(\left(10^{12}\,\text{eV}\right)\)

\(~100\,\text{photons/m}^2\)

130 m

5 ns

0.5°
Stereoscopic Arrays of Air Cherenkov Telescopes
VERITAS, Southern Arizona, USA, since January 2007
A possible design for a future array (CTA):

97 tel.

100m

600m

1000 m

100 m

100m²

600m²
Michelson stellar interferometry

1890: Measure of one of Jupiter's satellite diameter
1920: with Pease, Measure of Betelgeuse diameter (47 mas)

Fringe visibility

Degree of coherence

Intensity Fourier Transform

100 m @ 800 nm

8 nano-radians

1.6 milli-arcseconds

1930: 50 foot interferometer

1932: The technique is abandoned for being too difficult

Albert Michelson
1853-1931

Mount Wilson Hooker Telescope

with 20 foot Interferometer
\[ \delta = 30^\circ \]

6 telescopes => \( 6 \times 5/2 = 15 \) baselines
“Imaging the surface of Altair”  
Images of Capella (COAST)

September 13\textsuperscript{th} 1995

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{capella1995_13}
\end{figure}

September 28\textsuperscript{th} 1995

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{capella1995_28}
\end{figure}

Images of Betelgeuse (COAST)

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{betelgeuse1997_700nm}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{betelgeuse1997_1290nm}
\end{figure}

700nm (1997) 1290nm (1997)
Robert Hanbury Brown, 1916-2002
1950: Intensity Interferometry
1953: Radio measurements of CasA and CygA
1955: Search light measurement of Sirius
1963: Measurement of Vega from Narrabri
1972: Narrabri interferometer stops

Fig. 8.1. (a) An aerial view of the stellar interferometer at Narrabri Observatory. (b) The general layout of the interferometer.
32 stars measured from Narrabri magnitudes < 2.5
0.41mas < diameters < 3.24mas
10 of them in the main sequence

<table>
<thead>
<tr>
<th>Star number</th>
<th>Star name</th>
<th>Type</th>
<th>( \theta_{UD} \pm \sigma )</th>
<th>( \theta_{LD} \pm \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>472</td>
<td>( \alpha ) Eri</td>
<td>B 3 (Vp)</td>
<td>1.89 ± 0.07</td>
<td>1.92 ± 0.07</td>
</tr>
<tr>
<td>1713</td>
<td>( \beta ) Ori</td>
<td>B 8 (Ia)</td>
<td>2.43 ± 0.05</td>
<td>2.55 ± 0.05</td>
</tr>
<tr>
<td>1790</td>
<td>( \gamma ) Ori</td>
<td>B 2 (III)</td>
<td>0.70 ± 0.04</td>
<td>0.72 ± 0.04</td>
</tr>
<tr>
<td>1903</td>
<td>( \epsilon ) Ori</td>
<td>B 0 (Ia)</td>
<td>0.67 ± 0.04</td>
<td>0.69 ± 0.04</td>
</tr>
<tr>
<td>1948</td>
<td>( \zeta ) Ori</td>
<td>O 9-5 (Ib)</td>
<td>0.47 ± 0.04</td>
<td>0.48 ± 0.04</td>
</tr>
<tr>
<td>2004</td>
<td>( \kappa ) Ori</td>
<td>B 0-5 (Ia)</td>
<td>0.44 ± 0.03</td>
<td>0.45 ± 0.03</td>
</tr>
<tr>
<td>2294</td>
<td>( \beta ) CMa</td>
<td>B 1 (II–III)</td>
<td>0.50 ± 0.03</td>
<td>0.52 ± 0.03</td>
</tr>
<tr>
<td>2326</td>
<td>( \alpha ) Car</td>
<td>F 0 (Ib–II)</td>
<td>6.1 ± 0.7</td>
<td>6.6 ± 0.8</td>
</tr>
<tr>
<td>2421</td>
<td>( \gamma ) Gem</td>
<td>A 0 (IV)</td>
<td>1.32 ± 0.09</td>
<td>1.39 ± 0.09</td>
</tr>
<tr>
<td>2491</td>
<td>( \alpha ) CMa</td>
<td>A 1 (V)</td>
<td>5.60 ± 0.15</td>
<td>5.89 ± 0.16</td>
</tr>
<tr>
<td>2618</td>
<td>( \epsilon ) CMa</td>
<td>B 2 (II)</td>
<td>0.77 ± 0.05</td>
<td>0.80 ± 0.05</td>
</tr>
<tr>
<td>2693</td>
<td>( \delta ) CMa</td>
<td>F 8 (Ia)</td>
<td>3.29 ± 0.46</td>
<td>3.60 ± 0.50</td>
</tr>
<tr>
<td>2827</td>
<td>( \eta ) CMa</td>
<td>B 5 (Ia)</td>
<td>0.72 ± 0.06</td>
<td>0.75 ± 0.06</td>
</tr>
<tr>
<td>2943</td>
<td>( \alpha ) CMi</td>
<td>F 5 (IV–V)</td>
<td>5.10 ± 0.16</td>
<td>5.50 ± 0.17</td>
</tr>
<tr>
<td>3165</td>
<td>( \xi ) Pup</td>
<td>O 5 (I)</td>
<td>0.41 ± 0.03</td>
<td>0.42 ± 0.03</td>
</tr>
<tr>
<td>3207</td>
<td>( \gamma ) Vel</td>
<td>WC 8 + O 9 (I)</td>
<td>0.43 ± 0.05</td>
<td>0.44 ± 0.05</td>
</tr>
<tr>
<td>3685</td>
<td>( \beta ) Car</td>
<td>A 1 (IV)</td>
<td>1.51 ± 0.07</td>
<td>1.59 ± 0.07</td>
</tr>
<tr>
<td>3982</td>
<td>( \alpha ) Leo</td>
<td>B 7 (V)</td>
<td>1.32 ± 0.06</td>
<td>1.37 ± 0.06</td>
</tr>
<tr>
<td>4534</td>
<td>( \beta ) Leo</td>
<td>A 3 (V)</td>
<td>1.25 ± 0.09</td>
<td>1.33 ± 0.10</td>
</tr>
<tr>
<td>4662</td>
<td>( \gamma ) Crv</td>
<td>B 8 (III)</td>
<td>0.72 ± 0.06</td>
<td>0.75 ± 0.06</td>
</tr>
<tr>
<td>4853</td>
<td>( \beta ) Cru</td>
<td>B 0-5 (III)</td>
<td>0.702 ± 0.022</td>
<td>0.722 ± 0.023</td>
</tr>
<tr>
<td>5056</td>
<td>( \alpha ) Vir</td>
<td>B 1 (IV)</td>
<td>0.85 ± 0.04</td>
<td>0.87 ± 0.04</td>
</tr>
<tr>
<td>5132</td>
<td>( \epsilon ) Cen</td>
<td>B 1 (III)</td>
<td>0.47 ± 0.03</td>
<td>0.48 ± 0.03</td>
</tr>
<tr>
<td>5953</td>
<td>( \delta ) Sco</td>
<td>B 0-5 (IV)</td>
<td>0.45 ± 0.04</td>
<td>0.46 ± 0.04</td>
</tr>
<tr>
<td>6175</td>
<td>( \xi ) Oph</td>
<td>O 9-5 (V)</td>
<td>0.50 ± 0.05</td>
<td>0.51 ± 0.05</td>
</tr>
<tr>
<td>6556</td>
<td>( \alpha ) Oph</td>
<td>A 5 (III)</td>
<td>1.53 ± 0.12</td>
<td>1.63 ± 0.13</td>
</tr>
<tr>
<td>6879</td>
<td>( \epsilon ) Sgr</td>
<td>A 0 (V)</td>
<td>1.37 ± 0.06</td>
<td>1.44 ± 0.06</td>
</tr>
<tr>
<td>7001</td>
<td>( \alpha ) Lyr</td>
<td>A 0 (V)</td>
<td>3.08 ± 0.07</td>
<td>3.24 ± 0.07</td>
</tr>
<tr>
<td>7557</td>
<td>( \alpha ) Aql</td>
<td>A 7 (IV, V)</td>
<td>2.78 ± 0.13</td>
<td>2.98 ± 0.14</td>
</tr>
<tr>
<td>7790</td>
<td>( \alpha ) Pav</td>
<td>B 2-5 (V)</td>
<td>0.77 ± 0.05</td>
<td>0.80 ± 0.05</td>
</tr>
<tr>
<td>8425</td>
<td>( \alpha ) Gru</td>
<td>B 7 (IV)</td>
<td>0.98 ± 0.07</td>
<td>1.02 ± 0.07</td>
</tr>
<tr>
<td>8728</td>
<td>( \alpha ) PsA</td>
<td>A 3 (V)</td>
<td>1.98 ± 0.13</td>
<td>2.10 ± 0.14</td>
</tr>
</tbody>
</table>

Fig. 2.4. Simplified outline of an intensity interferometer.
How does it work?

\[ I_A = K_A \left[ E_1 \sin(\omega_1 t + \phi_1) + E_2 \sin(\omega_2 t + \phi_2) \right]^2 \]

D.C. Component

\[ = \frac{1}{2} K_A \left[ (E_1^2 + E_2^2) - \left[ E_1^2 \cos 2(\omega_1 t + \phi_1) + E_2^2 \cos 2(\omega_2 t + \phi_2) \right] \right] \]

\[ = -2 E_1 E_2 \cos[(\omega_1 + \omega_2) t + (\phi_1 + \phi_2)] \]

\[ + 2 E_1 E_2 \cos[(\omega_1 - \omega_2) t + (\phi_1 - \phi_2)] \]

"Wave noise" selected by A.C. coupling

Fig. 2.5. Illustrating the principle of an intensity interferometer.

\[ I_A \approx K_A E_1 E_2 \cos[(\omega_1 - \omega_2) t + (\phi_1 - \phi_2)] \]

\[ I_B \approx K_B E_1 E_2 \cos[(\omega_1 - \omega_2) t + (\phi_1 - \phi_2) + \omega_1 d_1/c - \omega_2 d_2/c] \]
More generally:

* $c(d)$ is the squared Fourier transform of the light distribution across the source.

* With 3 or more telescope, it is possible to recover a model independent image

* require huge quantities of light

* only requires coherence time to be preserved $\rightarrow$ cheap optics

\[
    c(d) = \lim_{T \to \infty} \frac{1}{T} \int_0^T I_A(t) I_B(t) \, dt = K_A K_B E_1^2 E_2^2 \cos \left[ \frac{(\omega_1 d_1 - \omega_2 d_2)}{c} \right] \\
    c(d) \approx K_A K_B E_1^2 E_2^2 \cos \left[ \frac{\omega (d_1 - d_2)}{c} \right] = K_A K_B E_1^2 E_2^2 \cos \left[ \frac{\pi D \theta}{\lambda} \right]
\]
More generally:

* \( c(d) \) is the squared Fourier transform of the light distribution across the source.
* With 3 or more telescope, it is possible to recover a model independent image
* require huge quantities of light
* only requires coherence time to be preserved -> cheap optics
* Telescopes exist and are available
J.E. Grindlay, 1975 uses the Narrabri telescopes to observe Cen A in gamma TeV energies.

2008 we could start using TeV gamma ray telescopes as Intensity Interferometer receivers.
Air Cherenkov Telescopes as Intensity Interferometer

Interferometric observation during full moon
1km² square grid array of 81 telescopes 125m spaced: 81 x 80 / 2 = 3240 baselines!
$1 \text{ km}^2$ square grid array of 81 telescopes 125m spaced: $81 \times 80 / 2 = 3240$ baselines!
We (will) have the large arrays of light collectors, now, what do we do?

A modern intensity interferometer, taking advantage of technological developments since 1970!

* Photo-detection
* Signal processing
* Communication
Multi-Pixel Photon Counter (MPPC)
Geiger Avalanche Photo-Diode (G-APD)

- Small size (<5mm)
- Temperature sensitivity (2.5%/degree)
+ 60% Photo-detection efficiency
+ High internal gain \((10^5-10^6)\)
+ Small excess noise

A. Nepomuke Otte, 2007, 30th ICRC, Mexico
Digital Correlator

200MHz digitization prototype
1GHz Already possible

Diagram:
- Short Delays
- Phase Switch
- FADC
- Delay 2
- FPGA
- Multiplier
- \(\times (+1)/\times (-1)\)
- Delay 1
- Sum Register
- Computer Readout
Analog optical fiber system developed in Leeds

R. White, J. Rose, ...
Table top test bench
Two 3m telescopes on a 23m baseline at Bonneville Seabase, Grantsville Utah
**Sensitivity?**

\[(S/N)_{RMS} = A \cdot \alpha \cdot n \cdot |y|^2 \sqrt{\Delta f \cdot T / 2}\]

\[A = 100 \text{m}^2\]
\[\alpha = 30\%\]
\[\Delta f = 1 \text{GHz}\]
\[T = 5 \text{ hours}\]
\[S/N = 5\]
\[n \sim 6.7 \text{m} \quad \Delta r = 14\%\]
\[\text{at } 5 \text{m} \quad \Delta r = 3\%\]

This is with just one baseline!!!
With many baselines...

PSF limitation:
$0.05^\circ \rightarrow 9.6\,\text{m}$

$0.01^\circ \rightarrow 13.0\,\text{m}$
What could we do?

More or less the same science as regular Michelson interferometers with
* shorter wavelength
* longer baselines
* less contrast
* many baselines

Distances to Cepheid stars (60 Cepheids with $m_v < 8$)

Fast rotator Be stars (300 stars with $m_v < 8$)

Circum stellar material

W.-J. de Wit
50 pre-main sequence stars (PMS) with $m_V < 8$, less than 50pc away

With CTA

$m_V = 8$, $|\gamma|_2 = 0.5$

$\rightarrow$ S/N = 5 in 5 hours

$so \Delta|\gamma|_2 \sim 0.1$

$m_V = 5.5 \rightarrow \Delta|\gamma|_2 \sim 0.01$
Close Binary star example: Spica

Limb and gravity darkening, mutual irradiation, tidal distortion, non radial oscillation...

$\beta$ Lyrae
Conclusions

+ Projects involving <100 Telescopes each ~100m² in area
+ Available telescope time for interferometry: ~ 500h/year
+ New technology available for Intensity Interferometry
- Possible need for optimizing optics
- possible benefit from optimizing array geometry

To do list:
- Complete lab and existing telescope tests
- Identify synchronization/positioning limitation
- Understand non idealized noise limitations
  & high order (>2) analysis and capabilities
- Get people involved and get relevant communities in touch.