# Interferometry in the USA

History of interferometry in the US and recent developments

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# Timeline of Interferometers in the US

- A. Michelson: Lick Obs. 12-inch, 1890;  Mt. Wilson 100-inch, 1920-30
- Mark I/II/III, MIT/Harvard/CfA/USNO/NRL, Mt. Wilson, 1979/1982-84/1986-93
- Infrared Spatial Interferometer (ISI), UC Berkeley, Mt. Wilson, 1987-present
- IRMA, U. Wyoming, Laramie, 1990-92
- Navy (Prototype) Optical Interferometer (NPOI→ NOI), USNO, Flagstaff AZ, 1994-present
- Infrared Optical Telescope Array (IOTA), CfA/UMass, Mt. Hopkins, AZ, 1994-2006
- Palomar Testbed Interferometer (PTI), JPL, Mt. Palomar, 1995-2008
- CHARA, Georgia State U./NSF, Mt. Wilson, 2001-present
- Keck Interferometer, JPL, Mauna Kea, HI, 2001-present
- Large Binocular Telescope Interferometer (LBTI), U. Arizona/JPL/UVa/UMinn, Mt. Graham, AZ, 2011…
- Magdalena Ridge Observatory Interferometer (MROI), NM Tech, Socorro, NM, ~2013…

Note:  Years are “first fringes” to “last fringes”, approximate.
Ref.: P. Lawson, Notes on the history of Stellar Interferometry,  Appendix A, in Principles of Long Baseline Stellar Interferometry, P. Lawson, Ed., 1999.
Ref.:  C. Townes, M. Creech-Eakman, P. Hinz, personal communications; also relevant web sites.

# A. Michelson: Mt. Wilson 100-inch, 1920-30

## MEASUREMENT OF THE DIAMETER OF α ORIONIS WITH THE INTERFEROMETER[1]

By A. A. MICHELSON and F. G. PEASE

ABSTRACT

*Twenty-foot interferometer for measuring minute angles.*—Since pencils of rays at least 10 feet apart must be used to measure the diameters of even the largest stars, and because the interferometer results obtained with the 100-inch reflector were so encouraging, the construction of a 20-foot interferometer was undertaken. A very rigid beam made of structural steel was mounted on the end of the Cassegrain cage, and four 6-inch mirrors were mounted on it so as to reduce the separation of the pencils to 45 inches and enable them to be brought to accurate coincidence by the telescope. The methods of making the fine adjustments necessary are described, including the use of two thin wedges of glass to vary continuously the equivalent air-path of one pencil. Sharp fringes were obtained with this instrument in August, 1920.

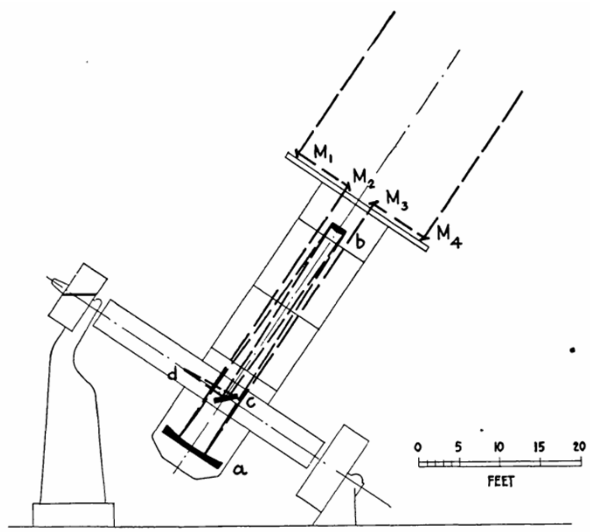



FIG. 1.—Diagram of optical path of interferometer pencils. $M_1$, $M_2$, $M_3$, $M_4$, mirrors; *a*, 100-inch paraboloid; *b*, convex mirror; *c*, coudé flat; *d*, focus.



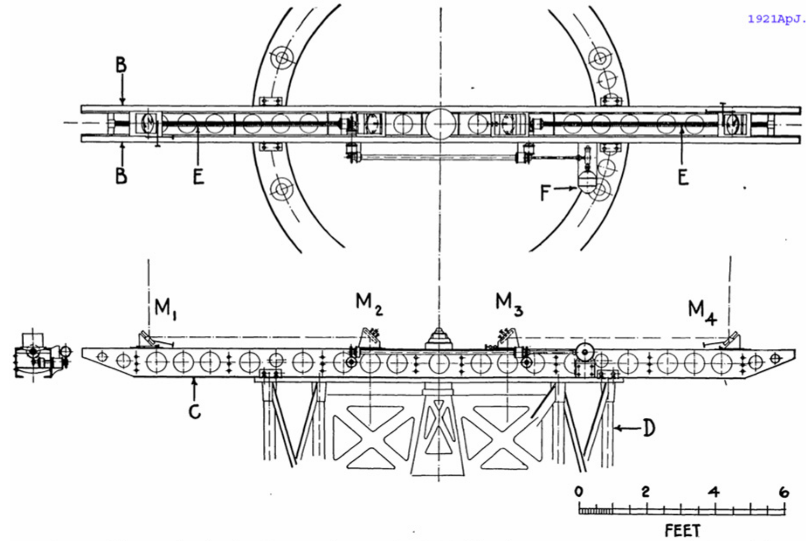
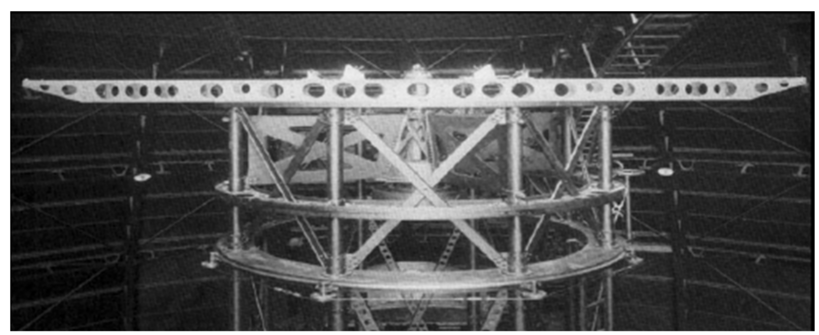



FIG. 2.—Diagram of 20-foot interferometer beam. $M_1$, $M_2$, $M_3$, $M_4$, mirrors; *B*, *B*, 10-inch channels; *C*, steel plate; *E*, *E*, screws to move outer mirrors; *F*, motor drive for screws; *D*, Cassegrain cage.

Assuming that the effective wave-length for α Orionis is λ 5750, its angular diameter from the formula $\alpha = 1.22\ \lambda/b$ proves to be 0″047; and with a parallax[1] of 0″018 its linear diameter turns out to be $240 \times 10^6$ miles, or slightly less than that of the orbit of Mars. This value corresponds to a uniformly illuminated disk, while for one darkened at the limb, this result, as mentioned above, would be increased by about 17 per cent. The uncertainty of the measurement of the angular diameter is about 10 per cent.



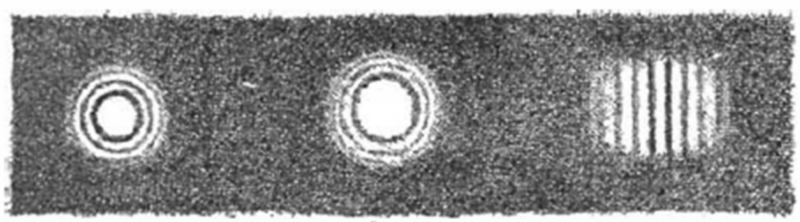
Ref.: Michelson and Pease, ApJ, 53, 249 (1921)
And http://www.chara.gsu.edu/CHARA/Slides/CHARAoverview.pdf

# A. Michelson: Lick Obs. 12-inch, 1890

## *MEASUREMENT OF JUPITER'S SATELLITES BY INTERFERENCE.*

IT has long been known that even in a telescope which is theoretically perfect, the image of a luminous point is composed of a series of concentric circles with a bright patch of light at the common centre. This system of circles can easily be observed by examining any bright star with a telescope provided with a circular diaphragm which diminishes the effective aperture. The appearance of the image is shown in Fig. 1, *a*. In the case of an object of finite angular magnitude the image could be constructed by drawing a system of such rings about every point in the geometrical image. The result for a small disk (corresponding to the appearance of one of the satellites of Jupiter as seen with a 12-inch telescope whose effective aperture

Fig 1



a b c

The general theory of these fringes may be found in the *Philosophical Magazine* for March 1891. The general equation showing the relation between the *visibility* of the fringes and the distance between the slits is

$$V^2 = \frac{\left[\int \phi(x) \cos kx\, dx\right]^2 + \left[\int \phi(x) \sin kx\, dx\right]^2}{\left[\int \phi(x)\, dx\right]^2} \quad . \quad (1)$$

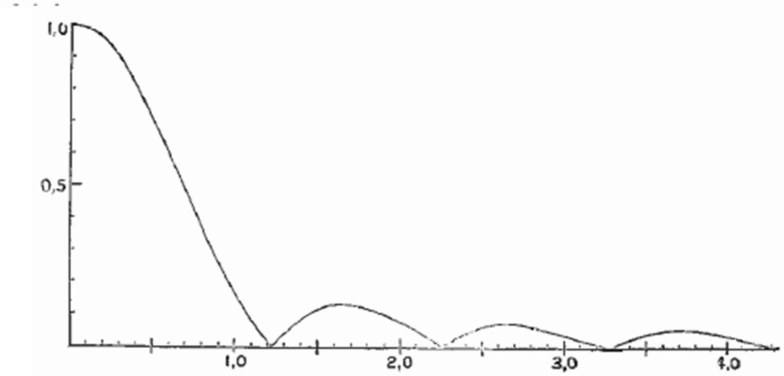



FIG. 2.

With this apparatus the satellites of Jupiter were measured, with results as given in the following table:—

TABLE I.

| No. of Satellites. | I. | II. | III. | IV. | Seeing. |
|---|---|---|---|---|---|
| | " | " | " | " | |
| August 2 ... | 1·29 ... | 1·19 ... | 1·88 ... | 1·68 ... | Poor. |
| August 3 ... | 1·29 ... | — ... | 1·59 ... | 1·68 ... | Poor. |
| August 6 ... | 1·30 ... | 1·21 .. | 1·69 ... | 1·56 ... | Poor. |
| August 7 ... | 1·30 ... | 1·18 ... | 1·77 ... | 1·71 ... | Good. |
| Mean... | 1·29 | 1·19 | 1·73 | 1·66 | |

Ref.: A. Michelson, Nature, 45, 160 (1891)

# Mark I/II/III, MIT/Harvard/CfA/USNO/NRL, Mt. Wilson, 1979/1982-84/1986-93

Mark III Interferometer c. 1985

Ref.: http://www.chara.gsu.edu/CHARA/Slides/CHARAoverview.pdf

# Mark I/II/III, MIT/Harvard/CfA/USNO/NRL, Mt. Wilson, 1979/1982-84/1986-93

## First fringe measurements with a phase-tracking stellar interferometer

Michael Shao and David H. Staelin

A prototype two-telescope stellar interferometer with a 1.5-m base line has been used to track the white-light fringes, 0.4–0.9 μm, from Polaris. Continuous fringe phase and amplitude measurements were made with ~220-photon/4-msec integration time and 1.27-cm$^2$ collecting area under 2-arc sec seeing conditions. The same control algorithm should be able to track fringes from an 8.7-mg star using the light from two 13-cm (5-in.) telescopes and a 10-msec integration time under 1-arc sec seeing conditions. When tracking, the servo maintained equal path lengths to 0.1-μm rms in the two arms of the interferometer, thus cancelling the path-length variations caused by earth rotation and atmospheric turbulence. In the future, two-color phase measurements will make optical aperture synthesis and optical very long-base-line astrometry possible.

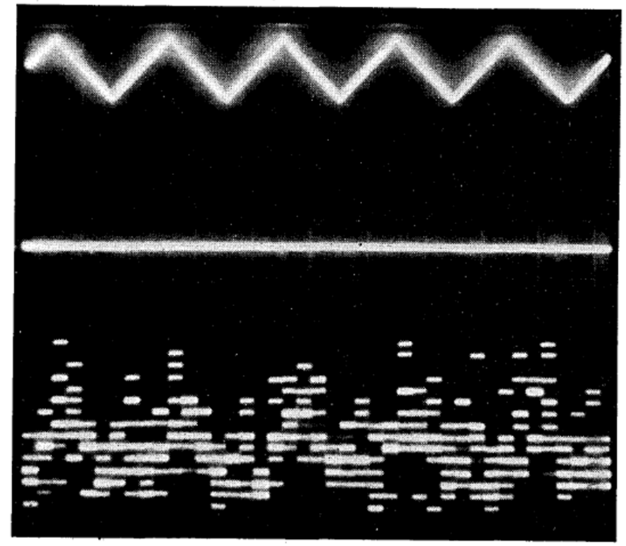


Fig. 3. Fringe detector phototube output.

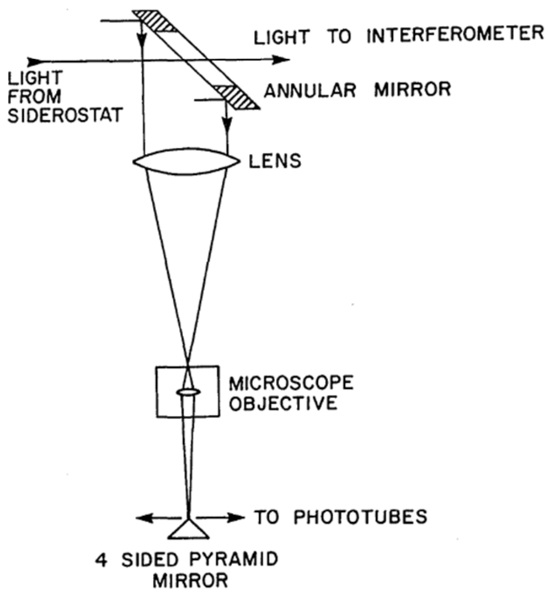



Fig. 2. Optical schematic of star trackers.

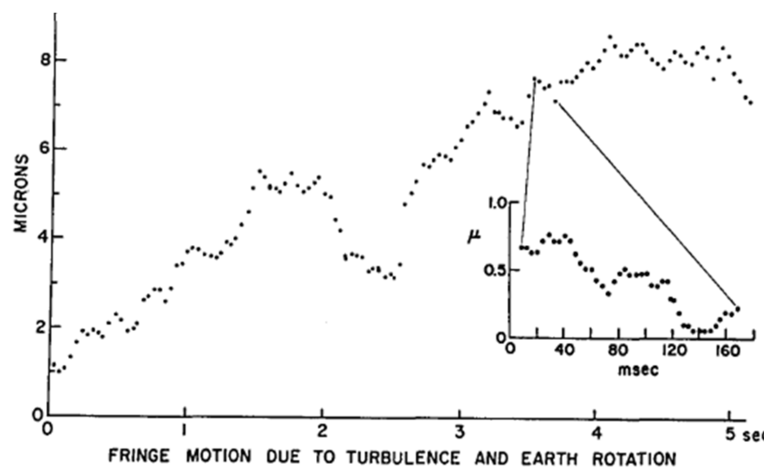
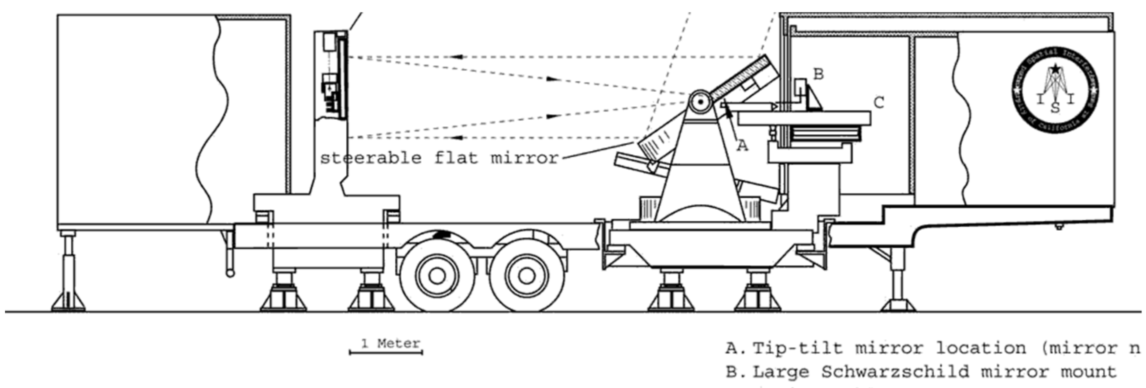
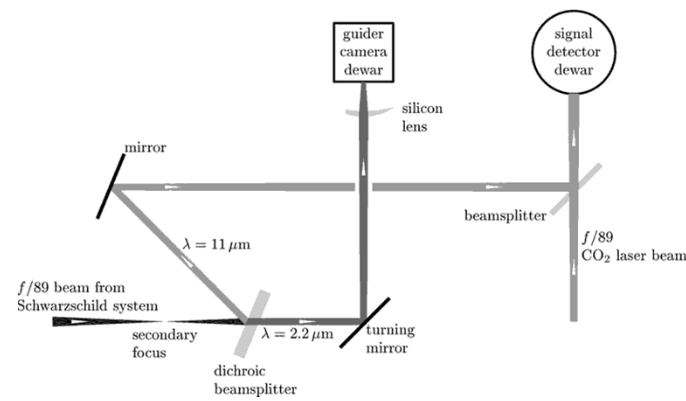



Fig. 4. Fringe motion due to turbulence observed 7 March 1979.

Ref.: Shao and Staelin, Applied Optics, 19, 1519 (1980)

# Infrared Spatial Interferometer (ISI), UC Berkeley, Mt. Wilson, 1987-present




Ref.: http://isi.ssl.berkeley.edu/system_overview.htm

# Infrared Spatial Interferometer (ISI), UC Berkeley, Mt. Wilson, 1987-present

## HIGH SPATIAL RESOLUTION 10 MICRON IMAGING OF IRC +10216

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*Received 1987 December 29; accepted 1988 March 18*

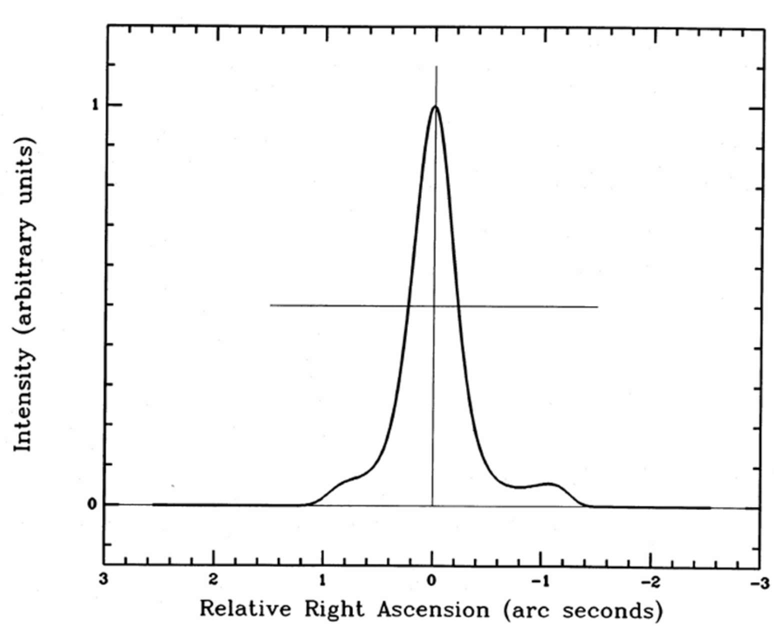


FIG. 2.—Deconvolved east-west profile of IRC +10216. The Richardson-Lucy iterative algorithm was applied to the data of Fig. 1, using the α Boo profile as the telescope point-spread function; this map is the result of 60 iterations. The central peak has FWHM ~ 0″.46, indicating that the true width of the central component is ~0″.40 when the residual point-spread width of the deconvolution procedure is removed (see discussion in text).

## The many faces of Betelgeuse

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**Abstract.**
The dynamics of the surface and inner atmosphere of the red supergiant star Betelgeuse are the subject of numerous high angular resolution and spectroscopic studies. Here, we present three-telescope interferometric data obtained at 11.15 μm wavelength with the Berkeley Infrared Spatial Interferometer (ISI), that probe the stellar surface continuum. We find striking variability in the size, effective temperature, and degree of asymmetry of the star over the years 2006–2009. These results may indicate an evolving shell of optically thick material close to the stellar photosphere.

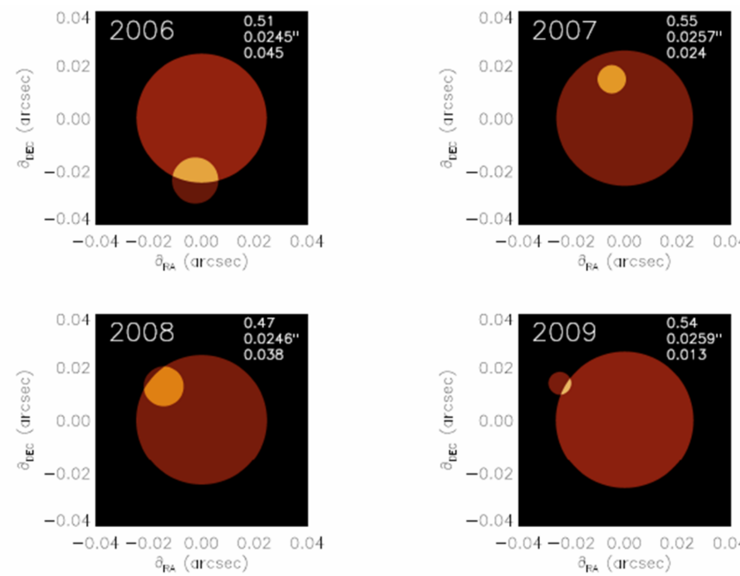


Figure 2. Depictions of the best-fit image models for Betelgeuse during each of the 2006, 2007, 2008 and 2009 epochs. Each figure includes the fit parameters: the fraction of the total flux from the star, the stellar radius in arcseconds, and the fraction of the total flux from the point. The point sources have been given the uniform disk sizes that they would have if they represented regions at a temperature of 7200 K. Our upper limit on the point source diameter is 20 mas.

Refs.: Bloemhov, et al, ApJ, 333, 300 (1988); Ravi et al, arXiv:1012.0377v1, (2010)

# Infrared Michelson Array (IRMA), U. Wyoming, Laramie, 1990-92

**THE INFRARED ANGULAR DIAMETER OF ALPHA HERCULIS MEASURED WITH A MICHELSON INTERFEROMETER**

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**IRMA: A Prototype Infrared Michelson Stellar Interferometer**

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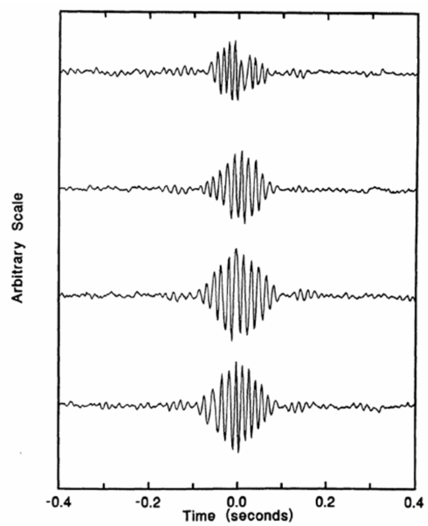



FIG. 1. Sequential examples of difference signal fringe packets.

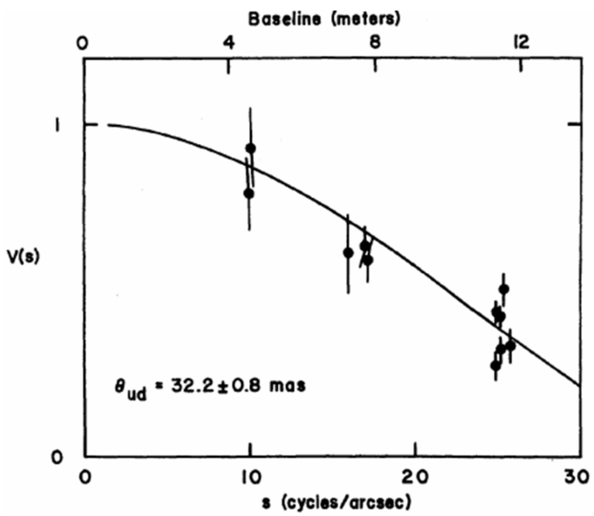



FIG. 2. Calibrated visibilities for $\alpha$ Her fit with a uniform disk model.

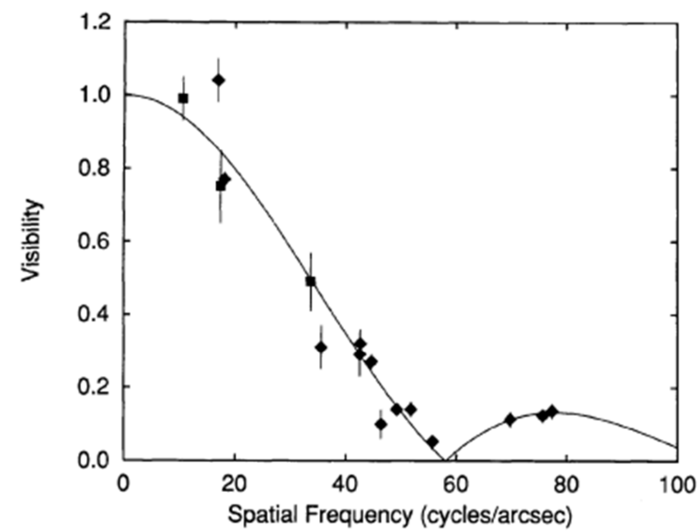
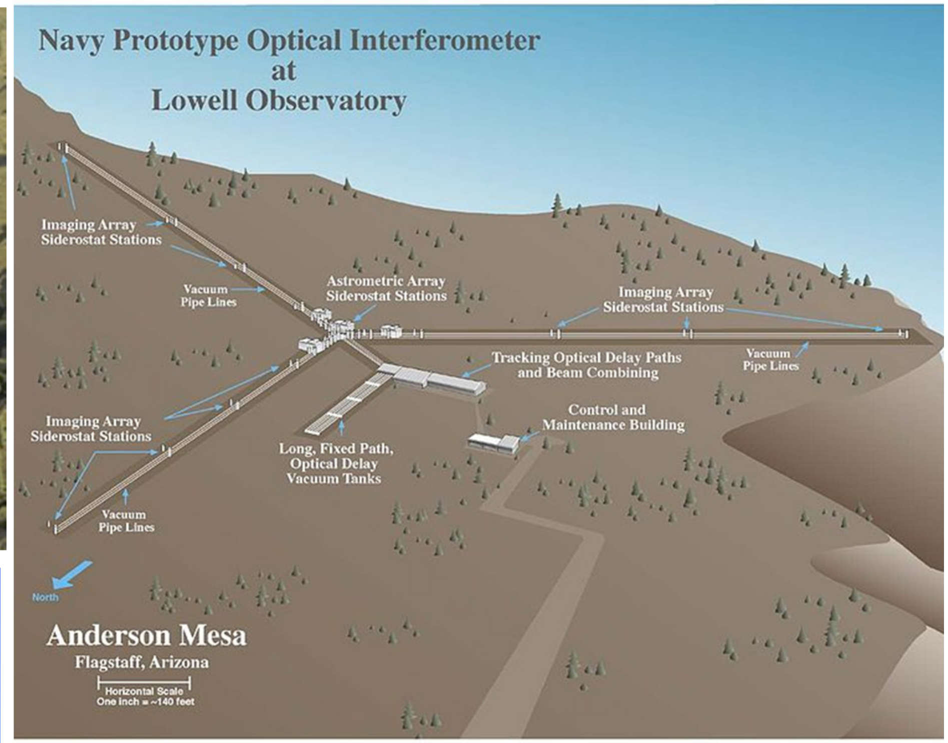
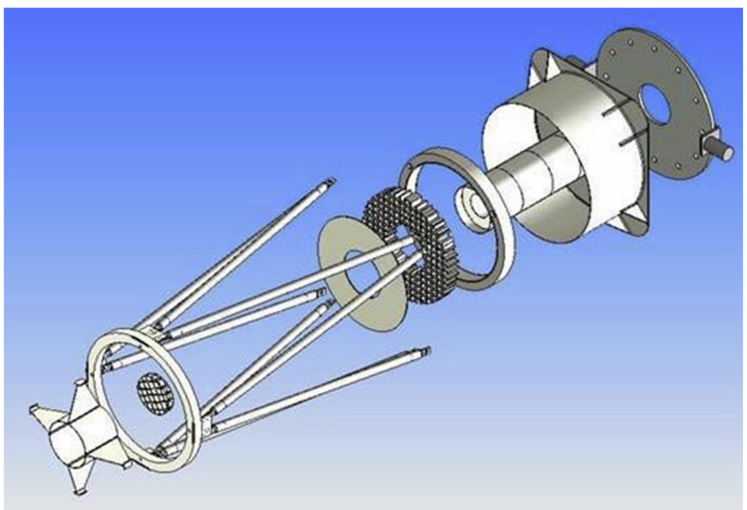



FIG. 6—Visibility data for $\alpha$ Boo. The filled squares (■) were obtained with IRMA and the filled diamonds (◆) were obtained with CERGA. The solid curve is a uniform-disk visibility function for an angular diameter $\theta_{ud} = 0.021$ arcsec.

Refs.: Benson et al, AJ, 102, 2091 (1991); Dyck et al, PASP, 105, 610 (1993)

# Navy (Prototype) Optical Interferometer (NPOI→ NOI), USNO, Flagstaff AZ, 1994-present



Ref.: http://en.wikipedia.org/wiki/Navy_Prototype_Optical_Interferometer

# Navy (Prototype) Optical Interferometer (NPOI→ NOI), USNO, Flagstaff AZ, 1994-present

THE NAVY PROTOTYPE OPTICAL INTERFEROMETER

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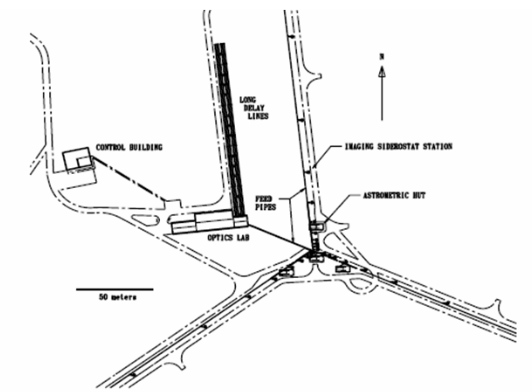


Fig. 4.—Plan view of the NPOI layout, showing imaging siderostat locations (filled circles), astrometric siderostat huts, roads, feed pipes, the optics laboratory, and the control building. The array arms extend beyond the area of the figure to a distance 250 m from the array center. The Lowell Observatory telescopes are just beyond the left edge of the figure.

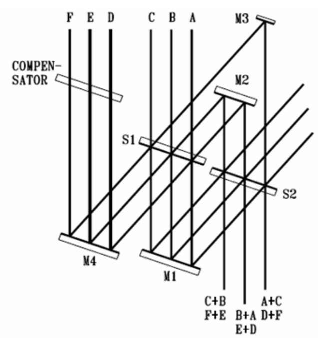


Fig. 9.—Schematic view of the beam combiner. Currently, the combiner works with three beams and combines them pairwise. The input beams (A, B, C) are split at beamsplitter S1. The reflected beams from S1 are shuffled by mirrors M2 and M3 and combined at S2 with the beams transmitted by S1 and reflected from M1. The combined beams (A + C, B + A, and C + B) transmitted by S2 are sent to the spectrometers. At present, the reflected beams from S2 are not used. The combiner will be converted to six-beam use by adding mirror M4. Six input beams (A, B, C, D, E, and F) will be combined into three output beams, each containing contributions from four inputs (A + C + D + F, B + A + E + D, and C + B + F + E). The compensator before M4 equalizes the optical paths in glass for all six input beams.

THE REVISED ORBIT OF THE $\delta$ Sco SYSTEM

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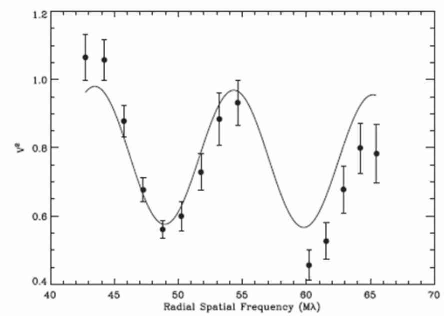



**Figure 1.** Squared visibility data obtained for $\delta$ Sco on 2006 June 5 across 14 spectral channels plotted as a function of radial spatial frequency. Data from only one scan and one baseline are plotted for clarity to illustrate the interferometric binary signature in the form of a cosine (solid line) that is used to obtain the angular separation and orientation of the binary components.

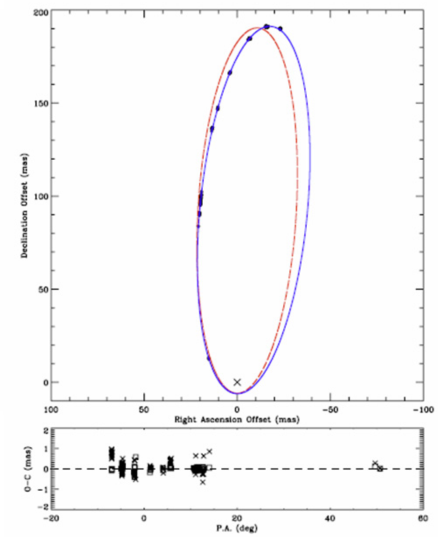
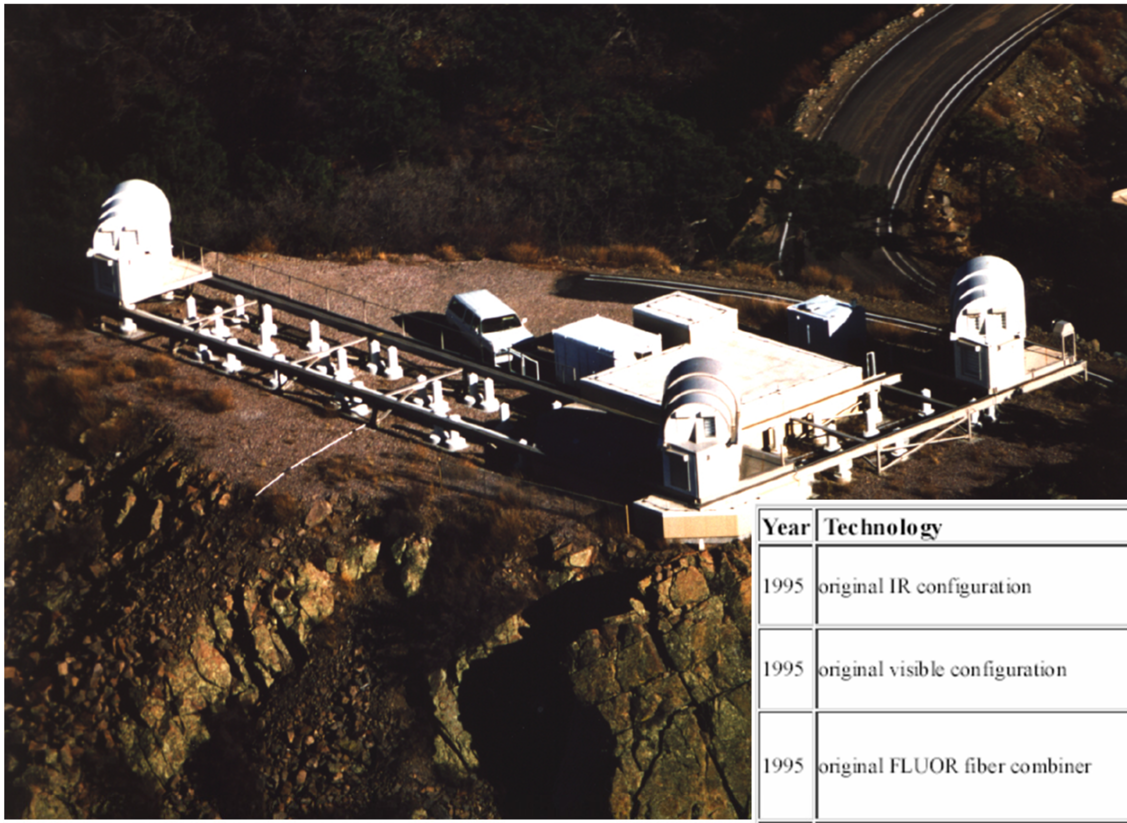



**Figure 2.** Top panel: binary orbits based on the parameters from Table 2 based on the best-fit parameters from this study (solid line) and those based on Tango et al. (dashed line) plotted with the astrometric results (filled circles) of Table 1. The uncertainty ellipses of the astrometric data are generally smaller than the size of the plotted symbols and were omitted for clarity. The location of the primary is marked with an "×." Bottom panel: the east–west (squares) and north–south (crosses) components of the O – C vectors as a function of the P.A. of the secondary.

Refs.: Armstrong et al, ApJ, 496, 550 (1998); Tycner et al. ApJL, 729, L5 (2011)

# Infrared Optical Telescope Array (IOTA), CfA/UMass, Mt. Hopkins, AZ, 1994-2006



| Year | Technology | Characteristics | Science examples |
|---|---|---|---|
| 1995 | original IR configuration | InSb discrete detector<br>slow scan (0.03 Hz)<br>K-band | Mira diameters (10%, K=3)<br>effective temperature of K,M giants |
| 1995 | original visible configuration | 4 parallel channels.<br>VRI bands<br>512x512 SITe CCD | binary separation (V=7) |
| 1995 | original FLUOR fiber combiner | single-mode image fiber<br>beam-combination<br>discrete detector<br>K-band | Mira diameters (1%, K=1)<br>$T_{eff}$ to M8 (+/-50K)<br>L-band (2%, L=-2)<br>M-band tests |
| 1997 | NICMOS3 camera with classical beam combination | low read noise<br>co-added reads<br>2 pixels, 2 beams<br>JHK bands | HAeBe star disks (+/-5%, J,H=7, K=6)<br>Miras (+/-5%, J,H=7, K=6)<br>copy to CHARA |
| 1998 | rapid scan,<br>classical beam combination | fast scan (10 Hz)<br>stroke 60 micron<br>VRI, JHK bands | CI Cam diameters (+/-4%, H,K=4)<br>M dwarf masses (+/- 1%) |
| 1999 | NICMOS3 camera<br>and FLUOR combination | low read noise<br>4 pixels, 4 beams<br>slow (0.2 Hz) scan<br>K-band | SW Vir, asym. diameters (+/-2%)<br>*zeta*Gem, Cepheid (*phi* = 2 +/- 0.1 mas)<br>R Leo diameters (+/- 0.2%) |
| 2000 | 3rd telescope | 3 simultaneous baselines, phase-closure | ....... |

Ref.: http://tdc-www.harvard.edu/IOTA/

# Infrared Optical Telescope Array (IOTA), CfA/UMass, Mt. Hopkins, AZ, 1994-2006

SUB–ASTRONOMICAL UNIT STRUCTURE OF THE NEAR-INFRARED EMISSION FROM AB AURIGAE

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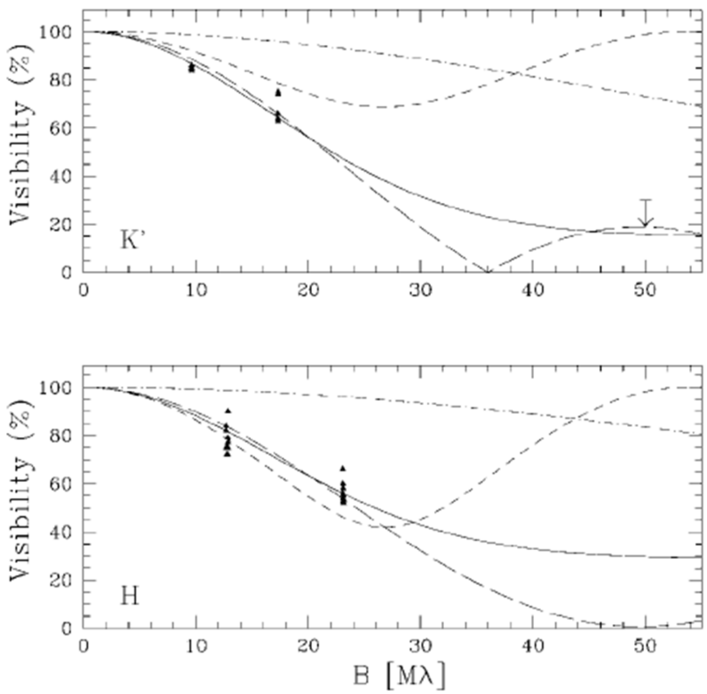


Fig. 1.—Visibility of AB Aur as a function of baseline length data and comparison with models of the source brightness distribution described in the text. The bottom panel shows the *H*-band data, and the top panel shows the *K'*-band data. The *K'* panel also shows the upper limit corresponding to the PTI observation. The models are plotted as follows: Gaussian (*solid lines*); ring (*long-dashed lines*); binary (*dashed lines*); and accretion disk (*dash-dotted lines*). The Gaussian and ring models provide an acceptable fit to the visibility data.

## Hot exozodiacal dust resolved around Vega with IOTA/IONIC

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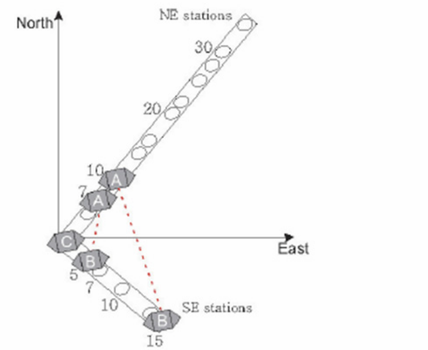
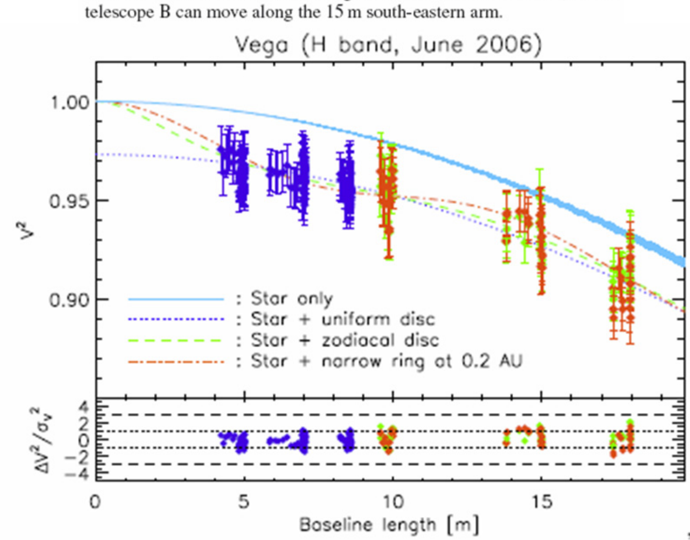
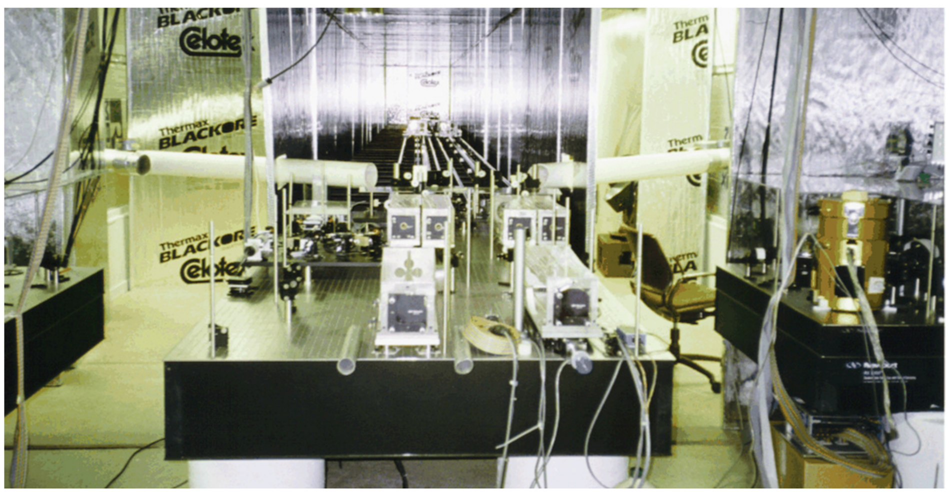


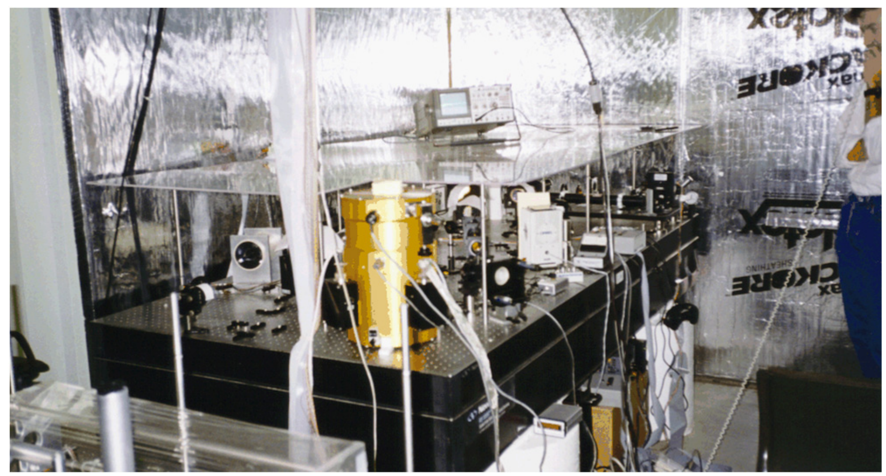

**Fig. 1.** Array geometry given with the available stations. Stations used during the observations are marked with a letter. Telescopes A and C can move on stations located along the 35 m north-eastern arm, while telescope B can move along the 15 m south-eastern arm.




Ref.: http://tdc-www.harvard.edu/IOTA/

# Palomar Testbed Interferometer (PTI), JPL, Mt. Palomar, 1995-2008



Refs.: http://nexsci.caltech.edu/missions/Palomar/tour2.html
http://en.wikipedia.org/wiki/Palomar_Testbed_Interferometer

# Palomar Testbed Interferometer (PTI), JPL, Mt. Palomar, 1995-2008

RADII AND EFFECTIVE TEMPERATURES FOR G, K, AND M GIANTS AND SUPERGIANTS

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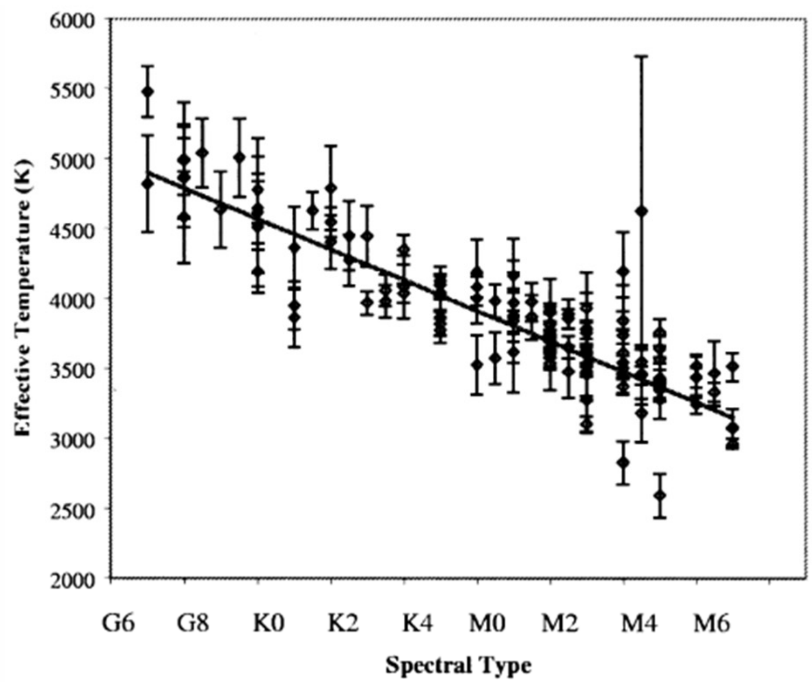


FIG. 1.—Temperature and radius as a function of spectral type. Data fr
and radii derived (Dyck et al. 1996, 1998) are plotted in all the figures.

HIGH-PRECISION ORBITAL AND PHYSICAL PARAMETERS OF DOUBLE-LINED SPECTROSCOPIC BINARY STARS—HD78418, HD123999, HD160922, HD200077, AND HD210027

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Received 2009 October 23; accepted 2010 June 16; published 2010 July 28

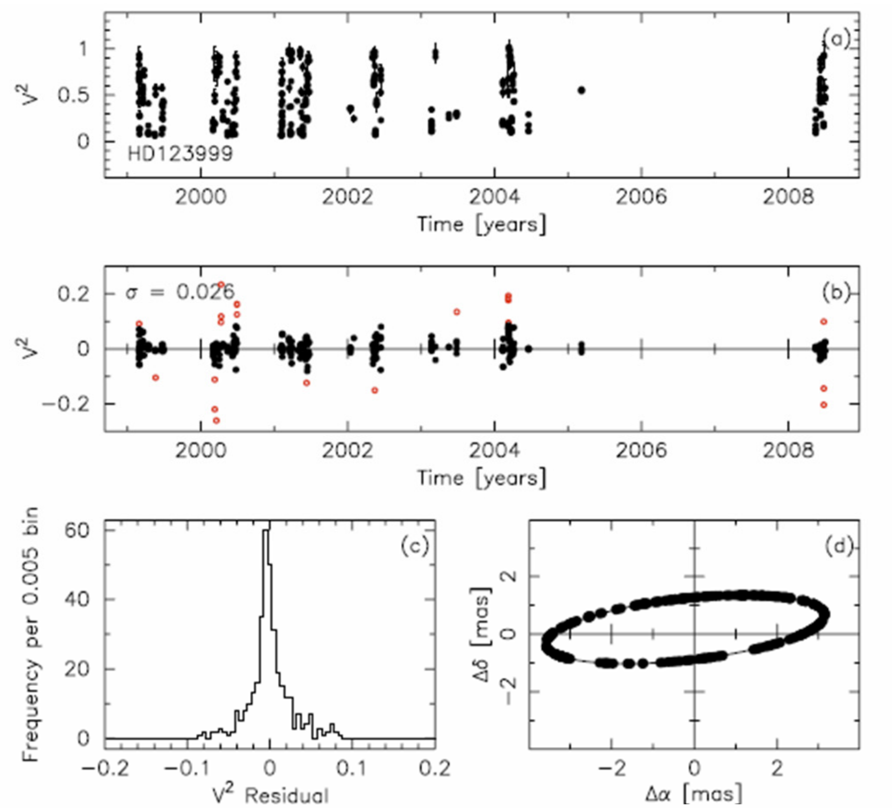
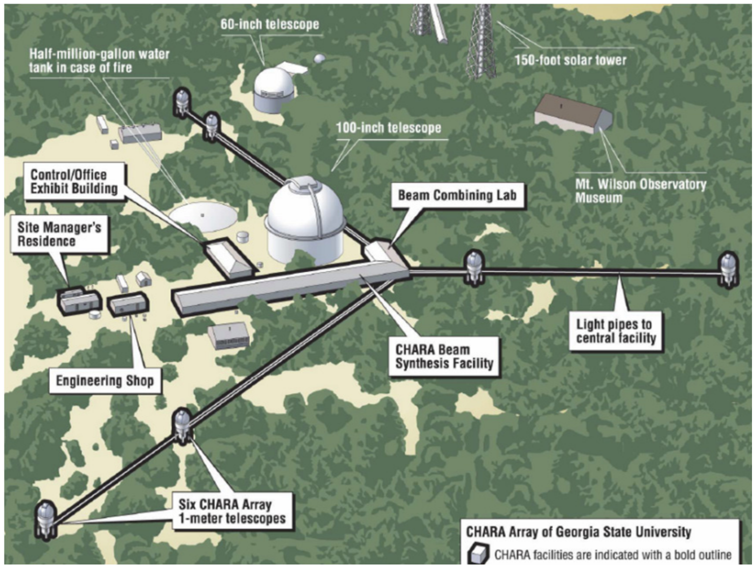
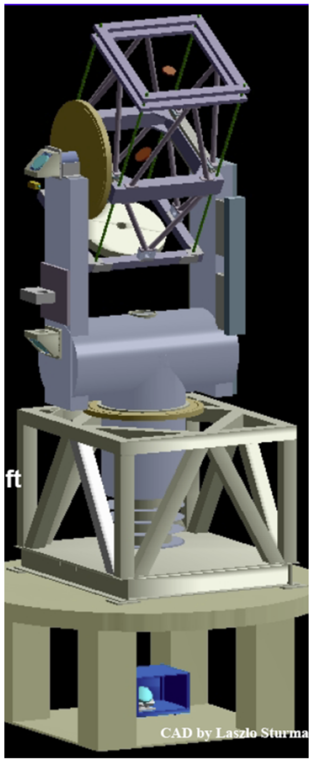


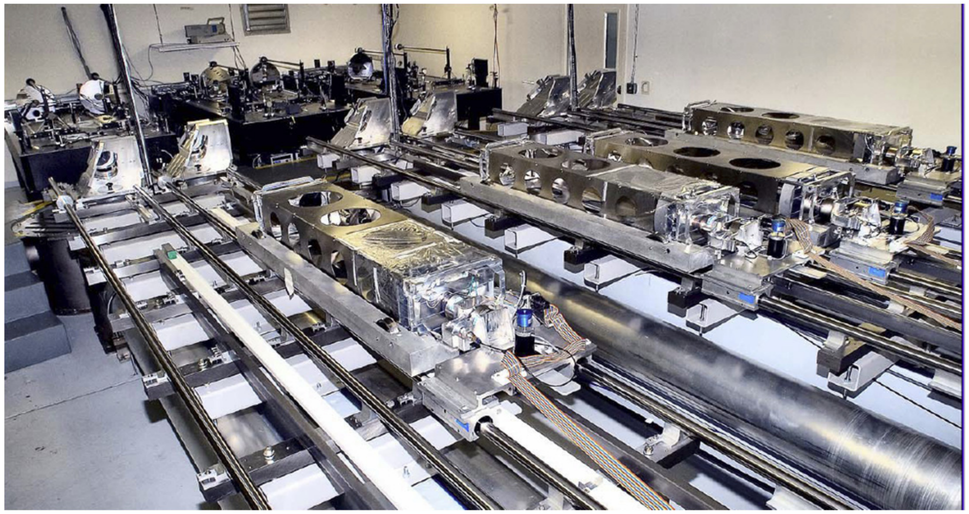

**Figure 11.** Visibility measurements of HD123999 as a function of time (a), their best-fit residuals as a function of time (b) and histogram (c). The measurements used to determine the best-fit orbital solution are denoted with filled circles. The corresponding orbital coverage and the relative orbit are shown in panel (d).

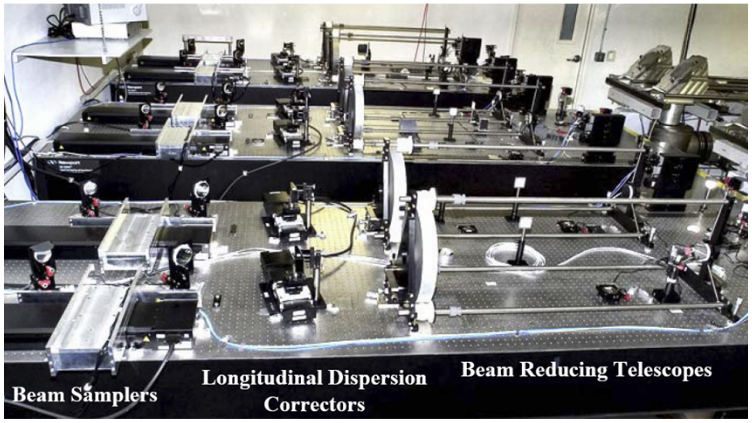
Refs.: Boden et al, AJ, 117, 521 (1999); Konacki et al, ApJ, 719, 1293 (2010)

# CHARA, Georgia State U./NSF, Mt. Wilson, 2001-present






Refs.: http://www.chara.gsu.edu/CHARA/Slides/CHARAoverview.pdf

# CHARA, Georgia State U./NSF, Mt. Wilson, 2001-present

FIRST RESULTS FROM THE CHARA ARRAY. V. BINARY STAR ASTROMETRY: THE CASE OF 12 PERSEI

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Stephen T. Ridgway
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Judit Sturmann, Laszlo Sturmann, Nils H. Turner, and David H. Berger
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Received 2005 October 7; accepted 2006 January 13

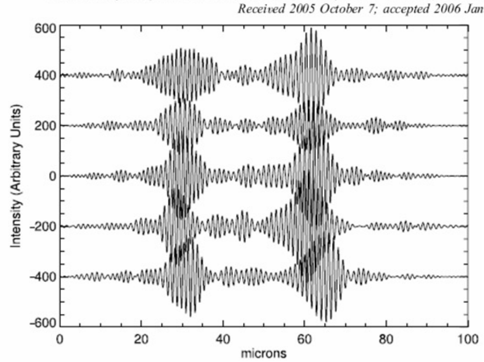



Fig. 1.—Five consecutive fringe scans of 12 Per, after filtering.

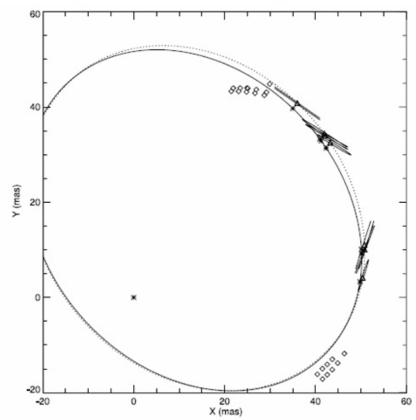



Fig. 5.—12 Per separations for all seven nights. The solid line represents the BSF98 orbit, and asterisks represent the standard locations during the nights. The dotted line represents the new orbit fit to the data, and the triangles represent the new orbit locations on the observing nights. The diamonds represent all the projected separations (21) derived from the seven nights. The error ellipses are plotted for each night's observation, as described in the text.

Toward Direct Detection of Hot Jupiters with Precision Closure Phase: Calibration Studies and First Results from the CHARA Array

M. Zhao[1], J. D. Monnier[2], X. Che[2], E. Pedretti[3], N. Thureau[3], G. Schaefer[4], T. ten Brummelaar[4], A. Mérand[5], S. T. Ridgway[6], H. McAlister[4], N. Turner[4], J. Sturmann[4], L. Sturmann[4], P. J. Goldfinger[4], C. Farrington[4]

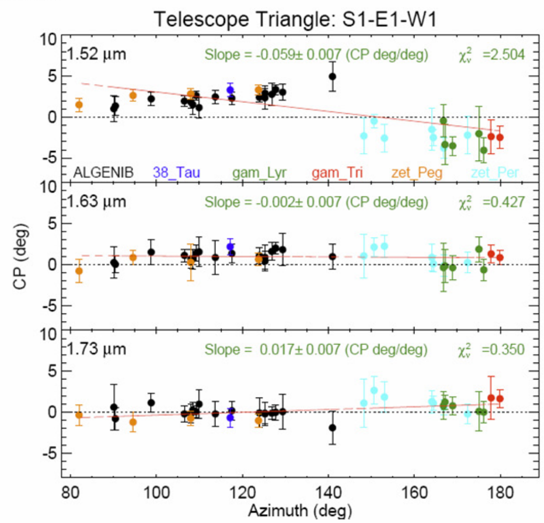



Fig. 3.— Closure phase vs. Azimuth for six calibrators in 2008 August. The first, middle and the last wavelength channels of MIRC are shown from top to bottom. The data were taken with telescope S1-E1-W1. The red line shows the linear fit of closure phase as a function of azimuth. Different colors indicate different targets. The slope of the linear fit and the reduced $\chi^2$ are also labeled in each panel.

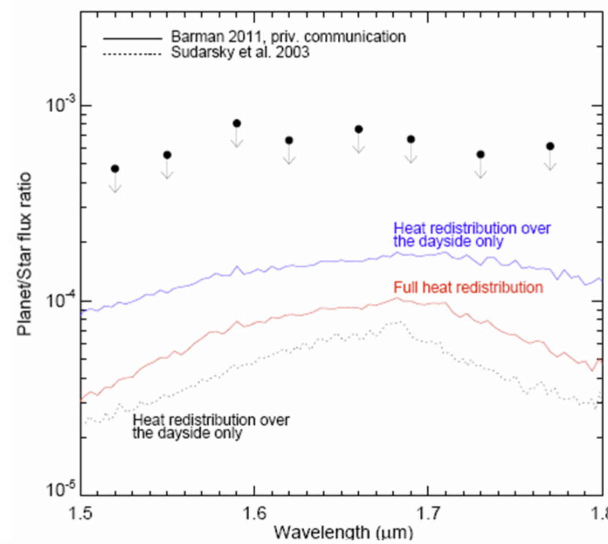
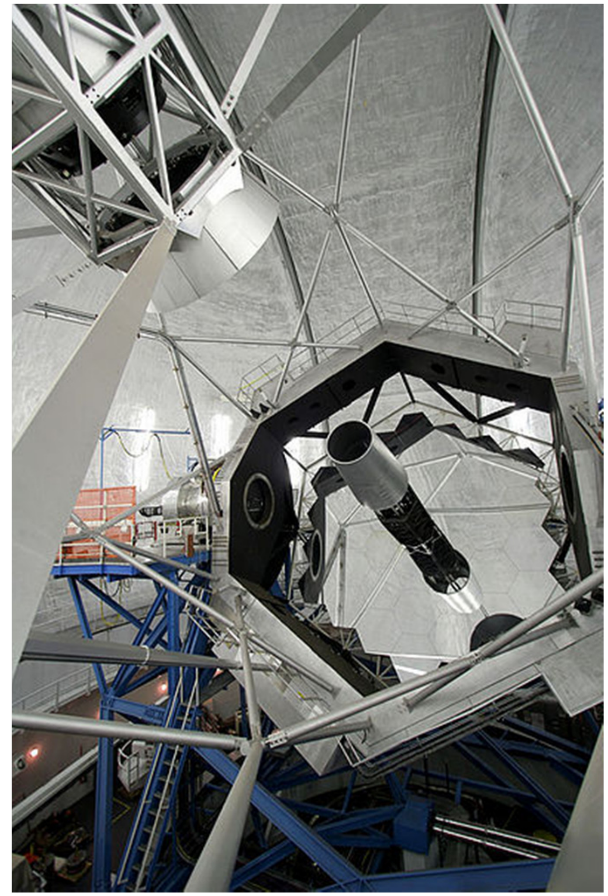



Fig. 9.— Upper limits with 90% confidence levels for the planet/star flux ratios of $\upsilon$ And b in the $H$ band, using the newly calibrated CHARA/MIRC data from multiple nights. The average upper limit level is $6 \times 10^{-4}$. The best channel at $1.52\mu m$ shows an upper limit flux ratio of $4.7\times10^{-4}$. The solid lines show the latest model based on Barman et al. (2005) (Barman 2011, private communication), assuming a typical radius of 1.3 $R_j$ for the planet. The blue line shows the model with incident flux uniformly distributed over the dayside of the planet only, while the red line shows the model with full heat redistribution over the entire sphere. The dotted line shows the model prediction from Sudarsky et al. (2003), assuming a radius of 1 $R_j$ with heat redistribution over the dayside only.

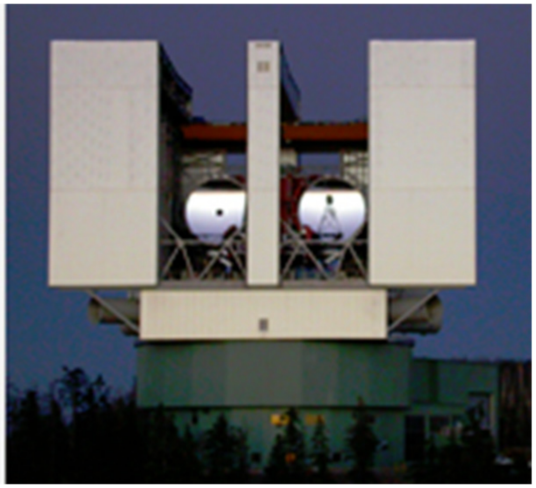
Refs.: Bagnulo et al, AJ, 131, 2695 (2006); Zhao et al, arXiv:1109.5183v1 (2011)

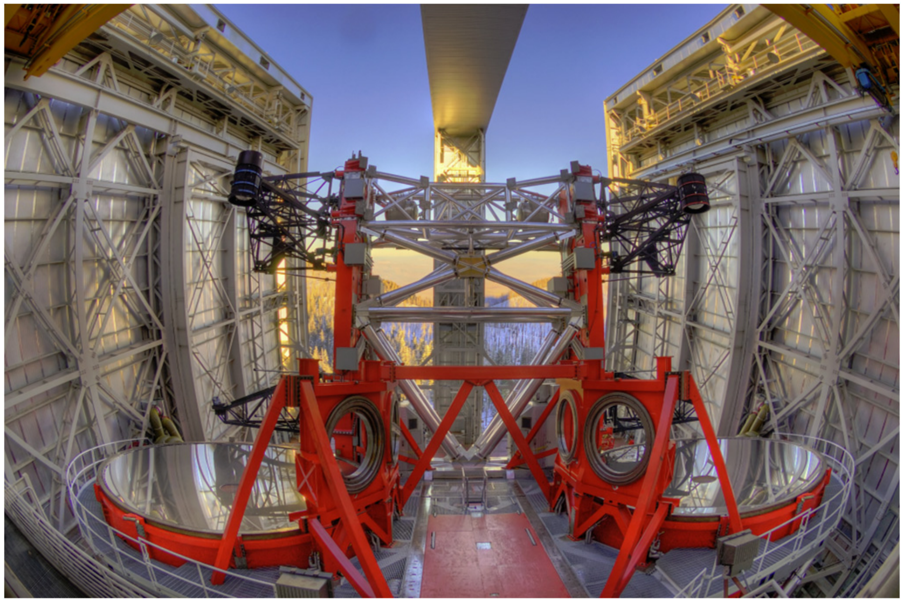
# Keck Interferometer, JPL,
# Mauna Kea, HI, 2001-present



Ref.: http://en.wikipedia.org/wiki/File:Kecknasa.jpg
http://planetquest.jpl.nasa.gov/Keck/keck_intro.cfm

Large Binocular Telescope Interferometer (LBTI), U. Arizona/JPL/UVa/UMinn, Mt. Graham, AZ, 2011…





Ref.: http://lbti.as.arizona.edu/LBTI-Main/Project.html

# Magdalena Ridge Observatory Interferometer (MROI), NM Tech, Socorro, NM, ~2013…

Ref.: http://en.wikipedia.org/wiki/Magdalena_Ridge_Observatory

# A Few Significant Conferences

- **IAUC 50, High Angular Resolution Stellar Interferometry, U. Maryland, 1978**

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- **Interferometry for Optical Astronomy II, Waikoloa, HI, 2002**

# A Few Significant Conferences

- **IAUC 50, High Angular Resolution Stellar Interferometry, U. Maryland, 1978**

  - *Connes, Dainty, Davis, Fried, Hanbury Brown, Koechlin, Low, Mertz, Ridgway, Roddier, Shao, Tango, Townes, Twiss, Weigelt, Worden, …*

- **Optical and Infrared Telescopes for the 1990s, KPNO, Tucson, 1980**

  - *Angel, Greenaway, Labeyrie, Meinel, Townes, Vakili, Woolf*

- **Michelson Summer School, Caltech, 1999**

  - *Lawson's book: McAlister, Boden, Townes, Quirrenbach, TenBrummelaar,, Colavita, Hutter, Dyck, Monnier, Mozurkewich, Armstrong, Serabyn, Ridgway*

- **Interferometry for Optical Astronomy II, Waikoloa, HI, 2002**
- **New Frontiers in Stellar Interferometry, Glasgow, 2004**

  *- 2 SPIE conferences, 5 volumes, 3308 pages of interferometry*

# Personal Epiphanies: 1/6

- **One photon at a time**

# Personal Epiphanies: 2/6

- One photon at a time

- **“Golden Rule”**

# Personal Epiphanies: 3/6

- One photon at a time
- “Golden Rule”
- **(Pupil densification, A. Labeyrie, violates rule)**

# Personal Epiphanies: 4/6

- One photon at a time
- “Golden Rule”
- (Pupil densification, A. Labeyrie, violates rule)
- **Sums of wavefront patches are the key to understanding**

# Personal Epiphanies: 5/6

- One photon at a time
- “Golden Rule”
- (Pupil densification, A. Labeyrie, violates rule)
- Sums of wavefront patches are the key to understanding
- **Same reflections for each wavefront patch**

# Personal Epiphanies: 6/6

- One photon at a time
- “Golden Rule”
- (Pupil densification, A. Labeyrie, violates rule)
- Sums of wavefront patches are the key to understanding
- Same reflections for each wavefront patch
- **Radio ≠ optical, owing to induced emission**