Binary Stars as Critical Tools & Tests
in Contemporary Astrophysics
Proceedings IAU Symposium No. 240, 2006
W.I. Hartkopf, E.F. Guinan & P. Harmanec, eds.

doi:10.1017/S1743921307003778

Overview of Multiple–Aperture Interferometry Binary Star Results from the Northern Hemisphere

Harold A. McAlister

Center for High Angular Resolution Astronomy, Georgia State University, Atlanta, GA, USA
email: hal@chara.gsu.edu

Abstract. Long-baseline optical interferometry (LBI) can nearly close the gap in selection space between astrometric and spectroscopic detection of binary star systems, bringing the complementary powers of astrometry and spectroscopy to bear on a complete dynamical understanding of such systems, particularly including the determination of the masses of the individual stellar components. In the case of double-lined spectroscopic systems, their resolution by long-baseline interferometry also yields the orbital parallax and hence the luminosities of the individual stars. In some of these cases, the angular diameters of one or more components are accessible, and so a complete specification of a star in terms of its mass, radius and luminosity is made.

The northern hemisphere is now equipped with several interferometers of unprecedented capability in terms of their baseline sizes, numbers of telescopes and telescope apertures. These instruments, most notably the Palomar Testbed Interferometer at Mt. Palomar Observatory, have produced very significant results of a number of interesting systems fulfilling interferometry's promise to produce fundamental astrophysical data at levels of accuracy that challenge or confirm astrophysical theory.

This paper presents basic principles of long-baseline interferometric study of binary stars and summarizes results from northern interferometers with specific examples of their broad impact on binary star astronomy.

Keywords. instrumentation: high angular resolution, instrumentation: interferometers, stars: binary, stars: fundamental parameters.

---

1. Some Relevant Interferometry Basics

The simplest analog to a long-baseline interferometer employed in the observation of binary stars is the classic Young's double slit experiment in which fringes are detected from two point sources illuminating the slits at a wavefront tilt angle of θ corresponding to the angular separation of a binary system as seen on the sky. Each "star" gives rise to a sinusoid with peaks (or "fringes") separated by λ/B where B is the slit spacing or interferometric "baseline". The two fringe patterns exactly cancel when θ equals one half the fringe spacing, which occurs at $\lambda/2B$, $3\lambda/2B$, $5\lambda/2B$, etc. This forms a convenient definition for the limiting resolution of a two-element binary star interferometer as $\theta_{\rm lim} = \lambda/2B$. Notice that this compares favorably with the limiting resolution of full-aperture speckle interferometry as given by the Rayleigh criterion $\theta_{\rm lim} = 1.22\lambda/B$ where, in this case, B is the telescope aperture.

An interferometer operating within a finite spectral bandwidth will yield a fringe packet whose width is related to the coherence length $\lambda^2/\Delta\lambda$. The basic observable of an interferometer is the fringe "visibility" as originally defined by A. Michelson to be:

$$V = \frac{I_{\rm max} - I_{\rm min}}{I_{\rm max} + I_{\rm min}} \tag{1.1}$$

where $I_{\max}$ and $I_{\min}$ are the maximum and minimum values of the fringe packet. A typical experimental setup involves the simultaneous detection of fringe packets on the two sides of a beam splitter within which the interference occurs. Because those packets are 180° out of phase with each other, their difference forms the fringe signal and the visibility is given simply by the fringe amplitude once the fringe is normalized to its mean and subtracted by unity. For an excellent tutorial on interferometry, see the proceedings of the 1999 Michelson Summer School (published by the Jet Propulsion Laboratory and edited by P. Lawson) which are available at olbin.jpl.naxa.gov/intro/.

The interferometric visibility obtained for a binary star is a function of the binary star parameters (position angle θ, angular separation ρ, magnitude difference Δm), the angular diameters of the component stars (Θ_1, Θ_2), and the instrumental parameters (projected baseline length B, wavelength of observed passband λ, position angle on sky of projected baseline ψ). The analytic expression for visibility is:

$$V^2 = (1+\beta)^{-2}(\beta^2 {V_1}^2 + {V_2}^2 + 2\beta V_1 V_2 cos(\frac{2\pi B}{\lambda}\rho cos(\theta - \psi))) \tag{1.2}$$

where

$$\beta = 10^{0.4\Delta m} \tag{1.3}$$

and

$$V_{1,2} = 2\frac{J_1(\pi\Theta_{1,2}B/\lambda)}{\pi\Theta_{1,2}B/\lambda}. \tag{1.4}$$

J_1 is the Bessel function of first order. Clearly, interferometers observing binary stars by means of visibility measurements do not measure the simple binary parameters (ρ, θ) directly and so cannot contribute in the usual way to catalogs such as the Washington Double Star (WDS) catalog.

Systems with separations exceeding about 10 milliarcseconds (mas) will typically no longer have overlapping fringe packets at long baselines and so visibility measurements of their separations become meaningless. Instead, separation can be measured astrometrically from the displacement of the separated fringe packets. The ability to measure large Δm systems is limited by the precision with which visibility can be measured since the visibility curve approaches that of a single star as Δm increases. With these limitations in mind, the current interferometric arrays are capable of resolving binaries with separations down to about 0.2 mas, a limit strictly determined by the longest baseline and shortest operating wavelength. Interferometers with beam combiners that spatially filter interfering beams with fibers or pinholes can to push to Δm's as large as 4 to 5 magnitudes at the expense of sensitivity.

2. Pioneering Work at Mt. Wilson

2.1. *Aperture Masking the 100-inch Telescope*

Inspired by Michelson's successful application of stellar interferometry, George Ellery Hale invited Michelson to try out his technique on the 60- and 100-inch telescopes. Using simple masks, Michelson easily demonstrated fringes, and Mt. Wilson astronomer John Anderson expanded Michelson's approach by designing a visual interferometer with variable slit spacing and orientation that was suitable to the accurate measurement of stellar diameters and binary star geometry. With this instrument, Anderson resolved the double-lined spectroscopic binary Capella during the winter of 1919-20 and employed six observations to calculate the visual elements of the 104-day system. In this process, Anderson (1920) determined the individual masses of the giant components and the orbital parallax of the system. This historic combination of the complementary capabilities of spectroscopy and interferometry when applied to binary stars can only now be widely exploited by the current generation of long-baseline arrays.

Anderson's Mt. Wilson colleague Paul Merrill obtained additional observations of Capella and resolved κ UMa and ν^2 Boo for the first time in a seven-month series of observations begun in the fall of 1920 (Merrill 1922). He inspected an additional 85 stars and marginally suspected duplicity in five cases (δ Cnc, 10 LMi, o Leo, ϵ UMa and υ Sgr). Of these five, three were subsequently inspected by speckle interferometry and found to be single, o Leo was resolved by long-baseline interferometry at a separation too close for the 100-inch experiment, but a companion was found by speckle interferometry in the case of δ Cnc that would have demonstrated variable visibility to Merrill. While Merrill expressed doubt as to the "reality of the changes" in visibility, he went on to encourage others to observe them "as the double star work at the Mount Wilson Observatory has been discontinued." Thus ended, after a very promising start, high angular resolution measurements of binary stars at the 100-inch telescope where these objects would be ignored for 60 years until speckle observers came along. However, the elegant success of Anderson and Merrill's work did inspire the long-term and highly productive program of visual interferometry with an "eyepiece interferometer" by W.S. Finsen at the Union/Johannesburg Observatory in South Africa. Finsen's program continued nearly to the advent of speckle interferometry (Finsen 1964). Since neither of those techniques is "multiple aperture" in nature, nothing further will be said about them here.

2.2. *The Mount Wilson "Long-Baseline" Interferometers*

With intuition that the maximum baseline available from a 100-inch aperture was just on the verge of providing diameters of giant and supergiant stars, Michelson and F.G. Pease collaborated on the design and use of the "20-ft interferometer", a beam that fed light from two movable mirrors into the optical train of the Hooker telescope. The only application to binary stars with this remarkable instrument was related by Pease in brief notes describing the determination of the orbit of Mizar from eight observations obtained with angular separations as small as $0''.008$ (Pease 1925, 1927). Interestingly, Pease credited "Professor Russell" as contributing the orbital analysis, although Henry Norris Russell was not listed as a co-author on the paper. The 20-ft was retired shortly after the second publication appeared, wrapped in heavy canvas and stored in the rafters of the 100-inch telescope building. At the instigation of this writer, the instrument was "exhumed" on 20 May 1999 in preparation for its display in CHARA's interferometry exhibit hall on Mt. Wilson where it can now be seen mounted atop the original prime focus cage of the telescope.

The irresistible desire for higher resolution led Pease to build a 50-ft stand-alone interferometer. Sadly, that instrument never fulfilled expectation, no doubt the result of extrapolating beyond the then accessible engineering performance limits. One can only wonder, had the 50-ft been a success, how it might have impacted binary star astronomy as a substantial number of spectroscopic binaries would have yielded to its very high limiting resolution.

3. The Modern Contributing Interferometers

Long-baseline, binary star interferometry came of age as recently as the late 1980's when the Mark III interferometer, a joint venture of the U.S. Naval Observatory, the Naval Research Laboratory, the Smithsonian Astrophysical Observatory and the Massachusetts Institute of Technology, became operational on Mt. Wilson. Working at visible

Table 1. Northern Interferometers that have Contributed to Binary Star Astronomy

Facility	Site	No. of Elements	Element Aperture	Max. Baseline	Operating Wavelength	Operational Status
Mark III	Mt. Wilson	2(4)	15 cm	32 m	0.45-0.80 μm	1987-1992
COAST	Cambridge, UK	4	40	100	0.4-0.95 + 2.2	since 1991
IOTA	Mt. Hopkins	3	45	38	0.5-2.2	1993-2006
NPOI	Anderson Mesa	6	60	(435)	0.45-0.85	since 1995
PTI	Mt. Palomar	3	40	110	1.5-2.4	since 1995
CHARA	Mt. Wilson	6	100	331	1.5-2.4	since 1999
KI	Mauna Kea	2	1,000	85	1.25-10.0	since 2001

wavelengths, the Mark III's 32-m longest baseline was more than adequate to reaching into the domain of spectroscopic binaries. Many of the problems unique to long-baseline interferometry were definitively solved by the Mark III, and its successors have drawn heavily on this highly successful, if short-lived, instrument, which was closed in 1992 in favor of the construction by the Navy of a new much larger interferometer near Flagstaff, Arizona, the Navy Prototype Optical Interferometer (NPOI). NPOI, which became operational in 1995, will ultimately have baselines almost 15 times longer than those of the Mark III. Before the Mark III was closed, Cambridge University opened its Cambridge Optical Aperture Synthesis Telescope (COAST) and successfully achieved the goal of producing the first optical aperture synthesis image in 1996.

The Smithsonian's Infrared Optical Telescope Array (IOTA) was commissioned on Mt. Hopkins in 1993 and, regrettably, closed in 2006. While IOTA was not used extensively for binary star studies, it rather naturally turned to binaries to demonstrate its imaging capability in 2004 after a third telescope was added to the previously two-telescope interferometer. In 1995, Caltech and the Jet Propulsion Laboratory began observations with their Palomar Testbed Interferometer (PTI), a facility with a 110-m longest baseline that has yielded very fine analyses of a number of resolved spectroscopic binaries to be described in more detail below. Georgia State University's CHARA Array saw first fringes from Mt. Wilson in 1999 but only became routinely scheduled for science operations in 2004. The CHARA Array currently possesses the longest operational baselines in the world and is capable of resolving a very large fraction of cataloged SB's. Last, and clearly not least, is the Keck Interferometer (KI), which is now limited to the 85-m baseline separating the Keck I and Keck II telescopes. The long-anticipated addition of the "Outrigger" telescopes was thwarted in 2005 when NASA canceled that effort.

Additional interferometers in the northern hemisphere have been built in France, where Antoine Labeyrie and others were among those responsible for the rebirth of the field, but those instruments are not described here as they had limited or no application to binary star astronomy. One example of an important negative result was the inspection by Harmanec *et al.* (1996) of the complex system comprising β Lyr, which was found to be unresolved by the GI2T, located on the Calern plateau in southern France and operated until recently by the Nice Observatory. The negative result from the north-south baseline provided evidence for an east-west orientation of the orbital plane as indicated by polarimetric measurements. The facilities listed in chronological order of their "first fringes" date in Table 1 were selected because of their relevance to the topic at hand.

A survey of the literature is summarized in Table 2, which gives an account of the refereed papers dealing with binary stars that have appeared as of early 2006 from these interferometers. As will be emphasized below, a total of 32 papers describing some 40

Table 2. Binary Star Output of Northern Interferometers

Facility	No. of Papers	No. of Systems	Emphasis
Mark III	11	20	SB' with P > 100 days
COAST	1	1	First optical aperture synthesis images (Capella)
IOTA	2	3	Closure phase imaging
NPOI	5	5	SB's and first 6-telescope imagery
PTI	11	11	SB's and ultra-precise astrometry of binaries
CHARA	1	1	Precise astrometry of 12 Per - more to come!
KI	1	1	PMS binary

binary star systems is a very modest contribution considering the potential LBI has in this field. The majority of the published results is from two instruments: the Mark III and Palomar Testbed Interferometers. While the CHARA Array has not yet contributed much in this area, the reader can be assured that binary stars will receive considerable attention from Mt. Wilson in coming years.

4. Some Example Results

4.1. *Mark III Results*

The baselines of the Mark III interferometer made it ideally suited to the resolution of spectroscopic binaries with intermediate periods, and the instrument was productively used in that domain, clearly demonstrating the effectiveness of LBI in complementing the spectroscopy to yield three-dimensional orbit solutions and component masses. The first of a series of such studies was that of α And (Pan *et al.* 1992) in which the sub-milliarcsecond precision of LBI was demonstrated through the calculation of a semi-major axis of 24.15 ± 0.13 mas. Similarly, Armstrong *et al.* (1992a) resolved the SB2 binary ϕ Cyg, which had previously been resolved by speckle interferometry (McAlister 1982), and improved the semi-major axis determination by a factor of five. Just as Capella had played a role in the first interferometers on Mt. Wilson, it was ideally suited to a definitive orbit determination by the Mark III (Hummel *et al.* 1994). Again, compared with speckle interferometry, the higher resolution of the Mark III naturally led to significant improvement of the orbital elements. Interestingly, the Anderson and Merrill observations of Capella show separations consistently too small by a few mas, most likely due to the difficulty in determining the effective wavelength of the visual interferometry process.

Other Mark III studies were completed for: β Ari (Pan *et al.* 1990); the AB,C system within Algol (Pan *et al.* 1993); the K4 Ib + B5V spectroscopic and eclipsing binary ζ Aur (Bennett *et al.* 1996); the G8III system η And (Hummel *et al.* 1993); ζ^1 UMa and η Peg in combined Mark III and NPOI analyses (Hummel *et al.* 1998); and, most recently, in another joint Mark III / NPOI venture targeting the Hyades binary θ^2 Tau (Armstrong *et al.* 2006). In a single paper (Hummel *et al.* 1995), the orbits of seven spectroscopic binaries were determined (π And, θ Aql, ζ^1 UMa, 93 Leo, 113 Her, β Tri and δ Tri). A three-way partnership of data exploiting the Mark III, NPOI and PTI facilities led to a solution of the orbit of o Leo (Hummel *et al.* 2001). The legacy of the Mark III interferometer is a powerful one in that the instrument not only brought interferometry into the modern world but it set an excellent standard for the application of this technique to binary stars.

https://doi.org/10.1017/S1743921307003778 Published online by Cambridge University Press

4.2. *Interferometric Imaging of Binaries*

Binary stars serve as a natural target for optical aperture synthesis imaging, which was first achieved on interferometry's old friend Capella by Baldwin *et al.* (1996) in a beautiful demonstration of orbital motion over a ten-day period in the fall of 1995. This achievement was soon followed up at NPOI by the first multi-spectral channel binary images with good orbital coverage of the 20.54-day system ζ^1 UMa (Benson *et al.* 1997). Hummel *et al.* (2000) employed imaging in their discovery of a new companion to the massive O star ζ Ori A, which had originally been suspected from observations at the Narrabri Intensity Interferometer by Hanbury Brown *et al.* (1974). In a *tour de force* demonstration, (Hummel *et al.* 2003) employed all six NPOI light-collecting telescopes simultaneously to produce images of the 71-day and 13-yr components comprising the triple star system η Vir. Subsequent images have been produced at IOTA in its three-telescope configuration in the case of λ Vir (Monnier *et al.* 2004) and, yet again, for Capella (Kraus *et al.* 2005). Experiments in imaging binaries and triple systems is presently underway at the CHARA Array using the University of Michigan infrared beam combiner now capable of simultaneous four-way beam combination.

4.3. *Palomar Testbed Interferometer Results*

Constructed essentially by the same group that designed and built the Mark III interferometer, the Palomar Testbed Interferometer rather naturally followed in the scientific footsteps of its predecessor and immediately embarked on a productive program of binary star studies. The first effort was an important negative result by Boden *et al.* (1998) in which a search for a stellar companion to the exoplanet host star 51 Peg yielded no such companion. There quickly followed analyses of the RS CVn system TZ Tri by Koresko *et al.* (1998) and the SB2 systems ι Peg (Boden *et al.* 1999a) and 64 Psc (Boden *et al.* 1999b).

In an analysis of the equal mass system 12 Boo, Boden, Creech-Eakman & Queloz (2000) came to the surprising conclusion that one component was significantly more luminous than the other. This finding was confirmed five years later after the incorporation of additional visibilities and new radial velocities by Boden *et al.* (2005) with the determination that $M_1 = 1.44{\pm}0.02$, $M_2 = 1.41{\pm}0.02\ M_\odot$ and the luminosity difference is $0.50{\pm}0.09$ magnitudes. This system has apparently been caught at that instant at which the slightly more massive component is entering into its red giant phase and evolving rapidly from the main sequence, temporarily leaving behind its companion. In a related analysis, Boden *et al.* (2006) found the high proper motion binary HD 9939 traversing the Hertzsprung gap enabling them to date the system at $9.12{\pm}0.25$ Gyr.

Other PTI work on spectroscopic binaries includes: the thick disk old system HD 195987 (Torres *et al.* 2002); HD 6118 and HD 27483 (Konacki & Lane 2004) for which the latter possesses the smallest semi-major axis yet determined by LBI (1.2 mas); and, the Pleiades SB2 Atlas (HR 1178) (Pan, Shao & Kulkarni 2004) for which an orbital parallax was determined that resolved the apparent discrepancy between the Hipparcos parallax and stellar models in favor of the models.

PTI was specifically designed to perform differential astrometry in a "narrow angle" mode employing two delay lines per telescope. This has permitted the instrument to undertake a program of very precise astrometry of binaries that are otherwise too wide for LBI. Thus, the Palomar High-precision Astrometric Search for Exoplanet Systems (PHASES) is monitoring binaries that fall in the separation regime of speckle interferometry. Lane & Muterspaugh (2004) attained an accuracy of $\pm 16\ \mu$as for the system HD 171779 Accuracies approaching that quality have subsequently been attained for δ Equ (Muterspaugh *et al.* 2005) and κ Peg (Muterspaugh *et al.* 2006a), and the relative inclination of the orbital planes in the triple system V819 Her have recently been determined by Muterspaugh *et al.* (2006b).

Finally, members of the PTI collaboration have teamed with others to combine observations from the Keck Interferometer and the Hubble Space Telescope Fine Guidance Sensors to determine the masses to about 10% accuracy of the SB2 system comprising the B component of the quadruple pre-main-sequence star HD 98800 B (Boden *et al.* 2005).

4.4. *The CHARA Array Binary Star Program*

One of the major motivating factors for the CHARA Array was an extrapolation of CHARA's long-term binary star program from the regime of separation accessible to speckle interferometry down to angular separations two orders of magnitude smaller. CHARA's facility on Mt. Wilson only became routinely operational in 2005 and most of its initial work has not been on binary stars. The exception to date is the astrometric study of the speckle binary 12 Per by Bagnuolo *et al.* (2006) in which an accuracy of ± 25 μas was utilized to refine the orbital parameters for the system.

This study is based on the analysis of separated fringe packets arising from binaries that are too wide to have overlapping packets that are amenable to standard visibility analysis but are sufficiently close so as to be encompassed within a fringe scan. This allows us to search for companions in the range of about 7 to 70 mas, giving overlap into the speckle regime. The approach is also being used to look for binaries in other selected samples of stars and also to employ one component as the visibility calibrator for the other in the case of a triple system.

CHARA is collaborating with F. Fekel (Tennessee State University) and J. Tomkin (University of Texas) on combining visibilities and velocities for selected SB2 systems. As a result of this symposium, we are also exploring a similar collaboration with P. Harmanec and P. Koubsky of the Ondrejov Observatory.

5. Prospects

The advantages of resolving spectroscopic binaries and thereby determining their orbits three-dimensionally are well-known with the most complete results emanating from a resolved SB2. In that case, knowledge of the individual masses is joined by the determination of the "orbital parallax" (with the potential for greater accuracy than Hipparcos). If the magnitude difference is also available, as it is in the case of LBI, then the individual luminosities fall out of the solution as well. In some cases, LBI will also yield the angular diameter of one or both components. Thus, LBI has the potential for contributing to the fundamental stellar mass/luminosity and mass/radius relations.

The potential for resolving known SB's has been explored in the context of parallaxes by Vinter Hansen (1942) and resolution by speckle interferometry (McAlister 1976). In order to better understand the regime accessible by LBI, CHARA initiated a bibliographic update (Taylor, Harvin & McAlister 2003) of the known SB's to create an input catalog for observational planning. In the case of the longest baseline of the CHARA Array (331 m), we find that at the K-band infrared some 370 or 43% of SB1's and 250 (49%) of SB2's are potentially resolvable. In the V-band, these numbers increase to 500 (57%) SB1's and 360 (70%) SB2's. Thus, it is clear that only a small fraction of the potential has yet been tapped by LBI observers for extracting fundamental stellar parameters from binary stars. In many of these cases, however, modern radial velocity studies are needed to improve the accuracy of the spectroscopic orbits so that the most accurate stellar parameters are obtainable. The results to date, particularly those from the PTI, are showing the benefits of such active collaborations.

6. Conclusions

Long-baseline interferometry from the northern hemisphere, particularly resulting from the Mark III and Palomar Testbed interferometers, has made important contributions to extracting fundamental astrophysical parameters from binary stars with accuracies sufficient to challenge astrophysical theory. But, the technique has really just begun to realize the full extent of its potential for resolving spectroscopic binary systems whose exploitation by interferometry can best be achieved in partnership with modern, high-precision radial velocity and quantitative spectroscopy programs.

Acknowledgements

The author wishes to thank the SOC for its invitation to participate in this Symposium and Georgia State University and the U.S. National Science Foundation for the support of the design and construction of the CHARA Array and its ongoing scientific work. Ellyn Baines kindly assisted in preparing this document.

References

Anderson, J.A. 1920, *ApJ* 51, 263

Armstrong, J.T., Mozurkewich, D., Vivekanand, M., Simon, R.S., Denison, C.S., Johnston, K.J., Pan, X.P., Shao, M., & Colavita, M.M. 1992, *AJ* 104, 241

Armstrong, J.T., Hummel, C.A., Quirrenbach, A., Buscher, D.F., Mozurkewich, D., Vivekanand, M., Simon, R.S., Denison, C.S., & Johnston, K.J. 1992, *AJ* 104, 2217

Armstrong, J.T., Mozurkewich, D., Hajian, A.R., Johnston, K.J., Thessin, R.N., Peterson, D.M., Hummel, C.A., & Gilbreath, G.C. 2006, *AJ* 131, 2463

Bagnuolo, W.G., Taylor, S.F., McAlister, H.A., ten Brummelaar, T.A., Gies, D.R., Ridgway, S.T., Sturmann, J. Sturmann, J., Turner, N.H., & Berger, D.H. 2006, *AJ* 131, 2695

Baldwin, J.E., Beckett, M.G., Boysen, R.C., Burns, D., Buscher, D.F., Cox, G.C., Haniff, C.A., Mackay, C.D., Nightingale, N.S., Rogers, J., Scheuer, P.A.G., Scott, T.R., Tuthill, P.G., Warner, P.J. Wilson, D.M.A., & Wilson, R.W. 1996, *A&A* 306, L13

Bennett, P.D., Harper, G.M., Brown, A., & Hummel, C.A. 1996, *ApJ* 471, 454

Benson, J.A., Hutter, D.J., Elias, N.M., Bowers, P.F., Johnston, K.J., Hajian, A.R., Armstrong, J.T., Mozurkewich, D., Pauls, T.A., Rickard, L.J., Hummel, C.A., White, N.M., Black, D., & Denison, C.S. 1997, *AJ* 114, 1221

Boden, A.F., van Belle, G.T., Colavita, M.M., Dumont, P.J., Gubler, J., Koresko, C.D., Kulkarni, S.R., Lane, B.F., Mobley, D.W., Shao, M., & Wallace 1998, *ApJ* 504, L39

Boden, A.F., Koresko, C.D., van Belle, G.T., Colavita, M.M., Dumont, P.J., Gubler, J., Kulkarni, S.R., Lane, B.F., Mobley, D., Shao, M., & Wallace J.K. 1999, *ApJ* 527, 360

Boden, A.F., Lane, B.F., Creech-Eakman, M.J., Colavita, M.M., Dumont, P.J., Gubler, J., Koresko, C.D., Kuchner, M.J., Kulkarni, S.R., Mobley, D.W., Pan, X.P., Shao, M., van Belle, G.T., Wallace, J.K., & Oppenheimer, B.R. 1999, *ApJ* 527, 360

Boden, A.F., Creech-Eakman, M.J., & Queloz, D. 2000, *ApJ* 536, 880

Boden, A.F., Torres, G., & Hummel, C.A. 2005, *ApJ* 627, 464

Boden, A.F., Sargent, A.I.; Akeson, R.L., Carpenter, J.M., Torres, G., Latham, D.W., Soderblom, D.R., Nelan, E., Franz, O.G., & Wasserman, L.H. 2005, *ApJ* 635, 442

Boden, A.F., Torres, G., & Latham, D.W. 2006, *ApJ* 644, 1193

Finsen, W.S. 1964, *AJ* 69, 319

Hanbury Brown, R., Davis, J., & Allen, L.R. 1974, *MNRAS* 167, 121

Harmanec, P., Morand, F., Bonneau, D., Jiang, Y., Yang, S., Guinan, E.F., Hall, D.S., Mourard, D., Hadrava, P., Božić, H., Sterken, C., Tallon-Bose, I., Walker, G.A.H., McCook, G.P., Vakili, F., Stee, Ph., & Le Contel, J.M. 1996, *A&A* 312, 879

https://doi.org/10.1017/S1743921307003778 Published online by Cambridge University Press

Hummel, C.A., Armstrong, J.T., Quirrenbach, A., Buscher, D.F., Mozurkewich, D., Simon, R.S., & Johnston, K.J. 1993, *AJ* 106, 2486

Hummel, C.A., Armstrong, J.T., Quirrenbach, A., Buscher, D.F., Mozurkewich, D., & Elias, N.M. 1994, *AJ* 107, 1859

Hummel, C.A., Armstrong, J.T., Buscher, D.F., Mozurkewich, D., Quirrenbach, A., & Vivekanand, M. 1995, *AJ* 110, 376

Hummel, C.A., Mozurkewich, D., Armstrong, J.T., Hajian, A.R., Elisa, N.M., & Hutter, D.J. 1998, *AJ* 116, 2536

Hummel, C.A., White, N.M., Elias, N.M., Hajian, A.R. & Nordgren, T.E. 2000, *ApJ* 549 L93

Hummel, C.A., Carquillat, J.-M., Ginestet, N., Griffin, R.F., Boden, A.F., Hajian, A.R., Mozurkewich, D., & Nordgren, T.E. 2001, *AJ* 121, 1623

Hummel, C.A., Benson, J.A., Hutter, D.J., Johnston, K.J., Mozurkewich, D., Armstrong, J.T., Hindsley, R.B., Gilbreath, G.C., Rickard, L.J., & White, N.M. 2003, *AJ* 125, 2630

Konacki, M., & Lane, B.F. 2004, *ApJ* 610, 443

Koresko, C.D., van Belle, G.T., Boden, A.F., Colavita, M.M., Creech-Eakman, M.J., Dumont, P.J., Gubler, J., Kulkarni, S.R., Lane, B.F., Mobley, D.W., Pan, X.P., Shao, M., & Wallace, J.K. 1998 *ApJ* 509, L45

Kraus, S., Schloerb, F.P., Traub, W.A., Carleton, N.P., Lacasse, M., Pearlman, M., Monnier, J.D., Millan-Gabet, R., Berger, J.-P., Hanuenauer, P., Perraut, K., Kern, P., Malbet, F., & Labeye, P. 2005, *AJ* 130, 246

Lane, B.F., & Muterspaugh, M.W. 2004, *ApJ* 601, 1129

McAlister, H.A. 1976, *PASP* 88, 317

McAlister, H.A. 1982, *AJ* 87, 563

Merrill. P.W. 1922, *ApJ* 56, 40

Monnier, J.D., Traub, W.A., Schloerb, F.P., Millan-Gabet, R., Berger, J.-P., Pedretti, E., Carleton, N.P., Kraus, S., Lacasse, M.G., Brewer, M., Ragland, S., Ahearn, A., Coldwell, C., Haguenauer, P., Kern, P., Labeye, P., Lagny. L., Malbet, F., Malin, D., Maymounkov, P., Morel, S., Papaliolios, C., Perraut, K., Perlman, M., Porro, I.L., Schanen, I., Souccar, K., Torres, G., & Wallace, G. 2004, *ApJ* 602, L57

Muterspaugh, M.W., Lane, B.F., Konacki, M., Wiktorowicz, S., Burke, B.F., Colavita, M.M., Kulkarni, S.R., & Shao, M. 2005, *AJ* 130, 2866

Muterspaugh, M.W., Lane, B.F., Konacki, M., Wiktorowicz, S., Burke, B.F., Colavita, M.M., Kulkarni, S.R., & Shao, M. 2006a, *ApJ* 636, 1020

Muterspaugh, M.W., Lane, B.F., Konacki, M., Wiktorowicz, S., Burke, B.F., Colavita, M.M., Kulkarni, S.R., & Shao, M. 2006b, *A&A* 446, 723

Pan, X.P., Shao, M., Colavita, M.M., Mozurkewich, D., Simon, R.S., & Johnston, K.J. 1990, *ApJ* 356, 641

Pan, X., Shao, M., Colavita, M.M., Armstrong, J.T., Mozurkewich, D., Vivekanand, M., Denison, C.S., Simon, R.S., & Johnston, K.J. 1992 *ApJ* 384, 624

Pan, X., Shao, M., & Colavita, M.M. 1993, *ApJ* 413, L129

Pan, X.P., Shao, M., & Kulkarni, S.R. 2004, *Nature* 427, 326

Pease, F.G. 1925, *PASP* 37, 155

Pease, F.G. 1927, *PASP* 39, 313

Taylor, S.F., Harvin, J.A., & McAlister, H.A. 2003, *PASP* 115, 609

Torres, G., Boden, A.F., Latham, D.W., Pan, M., & Stefanik, R.P. 2002, *AJ* 124, 1717

Vinter-Hansen, J.M. 1942, *PASP* 54, 137

Discussion

Robert Wilson: What about the narrowness of filters used by the various groups - are they mainly the same or not? Are they Johnson filters or Strömgren or what? Can you comment on tradeoffs (limiting magnitude, good definition of $\lambda_{\rm eff}$, etc.)?

https://doi.org/10.1017/S1743921307003778 Published online by Cambridge University Press

McAlister: The various groups do use standard filters. In CHARA's case, we currently use near-infrared filters at the H and K bands, where we presently have a limiting magnitude of +6.5 or 7.0, depending on seeing conditions. We expect these limits to improve. We can measure the effective filter wavelengths by observing in an FTS mode.