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INTRODUCTION TO THE SPECIAL ISSUE ON OPTICAL AND INFRARED INTERFEROMETRY

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After nearly one and a half centuries of effort, one of the most pernicious problems in observational astronomy — obtaining resolved images of the stars — is finally yielding to advances in modern instrumentation. The exquisite precision delivered by today's interferometric observatories is rapidly being applied to more and more branches of optical astronomy. The most capable interferometers in the Northern Hemisphere, both located in the United States are the Navy Precision Optical Interferometer (NPOI) in Arizona and the Center for High Angular Resolution Astronomy Array (CHARA) run by Georgia State University and located in California. In early 2013 these two groups held a joint meeting hosted by the Lowell Observatory in Flagstaff. All major groups working in the field were represented at this meeting and it was suggested to us by this Journal that this was an excellent opportunity to put together a special issue on interferometry. In order to be as broad as possible, those who did not attend the CHARA/NPOI meeting were also solicited to make a contribution. The result is this collection of papers representing a snap shot of the state of the art of ground based optical and near infrared interferometry.

Keywords: Interferometry, proceedings, beam combiner.

1. A Brief History of Long Baseline Optical Interferometry

1.1. *The dawn of stellar interferometry*

The 19th century witnessed spectacular progress in our understanding of light with the culmination of more than 150 years of debate raging over whether light was composed of particles or waves. Of central relevance to the most basic questions about the nature of light was the newly-minted technique of *Interferometry*. With the wave-theory strongly ascendant, the science of interferometry hits its stride in the middle of the century with the work of Fizeau who, in 1851 (Fizeau, 1851) invented a device which addressed the leading scientific question of the day: to measure the speed of the earth through the luminiferous aether.

It is in this setting of the very first scientific applications for interferometry that Fizeau suggested in 1868 that it should be possible to measure the angular diameters of distant stars (Fizeau, 1868). Stellar interferometry therefore ranks among the earliest of all applications to which interferometric apparatus was harnessed. Experimental validation of Fizeau's idea came 4 years later at the Marseille's 80 cm reflector with the work of Edouard Stéphan. After another interval of 17 years, Albert Michelson mounted his comprehensive experimental

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campaign delivering the first actual stellar diameters from Mt. Wilson (Michelson & Pease, 1921), together with a description of the mathematical foundations of stellar interferometry. The history of this era is given with comprehensive clarity in Peter Lawson's essay (Lawson, 2000) on stellar interferometry.

In many senses, this turned out to be a false dawn for the field. As the more ambitious longer-baseline devices of Michelson and Pease in the 1920s and 1930s foundered upon a host of technical problems, it was realized that precise measurements of stellar diameters were simply beyond the technology of the day. So comprehensive was this defeat that it took a radical reformulation of the conceptual underpinnings of interferometry, in the form of the Intensity Interferometer of Hanbury Brown and Twiss, to breathe new life into the field (Brown & Twiss, 1958). Their ambitious large-aperture interferometer was commissioned in outback New South Wales, Australia fifty years — almost to the day — before the scientific meeting reported here, revolutionizing bright star astronomy with the first empirical temperature scale for hot stars (Hanbury Brown *et al.*, 1967, 1974) and the first fully constrained orbits and stellar properties for binary systems (Herbison-Evans *et al.*, 1971).

These successes immediately launched a new generation of optical stellar interferometers, although sensitivity limitations with the intensity interferometer architecture drove the field back into a reformulation of homodyne or direct detection. With the march of more than fifty years in technological prowess, time was now ripe to redress the problems of stability and precision control which beset and ultimately foiled the efforts of Michelson and Pease on Mt. Wilson in the late 1920s.

1.2. *Revitalization and refinement*

The era of modern optomechanics and computing power that began in the 1970s allowed the development of the 'toolkit' for modern interferometers. Developments worldwide at a host of testbeds refined the technical needs for subsystems such as laser metrology and beam combiners — in Europe with the I2T (Labeyrie, 1975) and COAST (Baldwin *et al.*, 1996) interferometers; in the US with the Mark I, II, III (Shao *et al.*, 1988), IRMA (Dyck *et al.*, 1993), and IOTA (Dyck *et al.*, 1995); and in Australia with SUSI (Davis *et al.*, 1999).

A good example of the trickle-down of the technology can be seen from the Mark III interferometer: the technological ancestry of that facility's delay lines can be traced directly from that facility to PTI (Colavita *et al.*, 1999), the Keck Interferometer (Vasisht *et al.*, 1998), CHARA (ten Brummelaar *et al.*, 2005), and NPOI (Benson *et al.*, 1997) — the common design has morphed subtly from site to site, but the basic 4-stage servo design is essentially unchanged.

Along the way, specialized applications of the technology were also explored — mid-IR homodyne operation, with the ISI (Hale *et al.*, 2000); dual-beam astrometry with PTI, (Shao & Colavita, 1992; Boden & Quirrenbach, 2008) later applied at Keck and VLTI (Haguenauer *et al.*, 2010); and fiber-fed integrated optics beam combiners with the FLUOR (Coudé du Foresto *et al.*, 1997) and IONIC (Lacour *et al.*, 2008) instruments at IOTA (later applied at CHARA, VLTI, and NPOI).

As the technology was developed, the scientific 'low-hanging fruit' led to a number of striking observations. LBI observations of circumstellar environments of late-type stars (Danchi *et al.*, 1994; Monnier *et al.*, 2004), Be stars (Quirrenbach *et al.*, 1997), and young stellar objects (Millan-Gabet *et al.*, 2001; Tuthill *et al.*, 2001; Eisner *et al.*, 2004) all produced heavily-cited works. Equally important were direct measures of the fundamental stellar parameters of effective temperature and linear radius for giants (Dyck *et al.*, 1998; Perrin *et al.*, 1998; van Belle *et al.*, 1999; Mozurkewich *et al.*, 2003), super-giants (van Belle *et al.*, 2009), and Mira variables (Haniff *et al.*, 1995; van Belle *et al.*, 1996); the first tentative steps towards stellar surface imaging can be found in the detection of the 'dusty pinwheel' WR104 (Tuthill *et al.*, 1999) and Altair's oblateness (van Belle *et al.*, 2001).

Overall, this body of work, spanning largely over the 1980s and 1990s, provided designers with the tools necessary for building the following generation of interferometers — the first generation of arrays intended for use by the general astronomy community.

2. Modern Facility-Class Instruments

The current generation of optical interferometers aim to increase the performance of such facilities on a variety of fronts: flexibility, sensitivity, operational reliability, and user-friendliness. A list of currently existing facilities is given in Table 1. We

Table 1. Current facilities.

Name	Apertures	#Combined	Baselines	Wavelengths	Location
SUSI	13 × 15 cm Fixed.	2	5–160 m (640 m)	V	Narrabri, Australia
ISI	3 × 165 cm Movable	3	5–80 m	MI	Mount Wilson, CA, USA
NPOI	6 × 12 cm Movable	6	7–79 m (437 m)	V	Anderson Mesa, AZ, USA
CHARA	6 × 1 m Fixed	6	34–341	V, NI	Mount Wilson, CA, USA
VLTI	4 × 8.2 m Fixed 4 × 1.8 m Movable	4	11–129 m	NI, MI	Cerro Paranal, Chile
LBTI	2 × 8.4 m Fixed	2	0–23 m	NI, MI	Mount Graham, AZ, USA
MROI	10 × 1.4 Movable	6	7–340 m	V, NI	South Baldy, NM, USA

Note: This table contains a very brief over view of existing facilities and those under construction at this time listed in order of their commissioning. Here the wavebands are Visible (V), Near Infrared (NI) and Mid-infrared (MI). Here visible light means a wavelength of 0.5–1 microns, near infrared is 1–3 microns and mid-infrared is around 10 microns. Note that the LBTI (Herbst & Hinz, 2004) is unlike the rest of those listed as it uses a combination of filled aperture and interferometry, and the ISI uses a heterodyne combination method similar to that used by radio interferometers. The LBTI has obtained fringes on the sky and will soon begin scientific operations. The MROI (Creech-Eakman *et al.*, 2010) plans to obtain first fringes on the sky in 2015.

should mention that one modern and large facility, the Keck Interferometer, has been closed down due to a lack of funding from NASA.

One of the main distinctions of the more modern facilities is the broad range of wavelengths used, the amount of spectral resolution, and the large range of beam combiners available. A beam combiner can be considered a 'back-end' instrument, very much like a spectrograph or camera on a standard telescope, and all modern facilities are designed to provide space and support for a range of beam combiners. For example, at this time the CHARA Array supports seven different beam combiners with wavelengths ranging from 0.5 to 2.3 microns and spectral resolutions ranging from 20 to 30,000.

The technology developed and science obtained with interferometry have advanced very quickly. For example, the illustration on the cover of this journal shows all the stars measured to date with Interferometers. Included here are only those stars whose diameter was measured to 5% or better, see (Boyajian *et al.*, 2013) and references therein. Not included are binary stars, rotating, and other objects for which a simple diameter and temperature has little meaning. The other data used in this plot is from photometry and Hipparcos distances. This plot shows the broad range of stellar types open to study with this technique. The inset on the top left is an image of the star α Cephei (Zhao *et al.*, 2009) made in the H band using an interferometer. Note the scale — this star has a diameter of only a few milliarcseconds. Imaging of this kind is now routine for ground based interferometers. Finally, Fig. 1 shows how quickly this advance in spatial resolution has taken place.

A review of other LBI accomplishments with these modern facilities is a litany of unique finds provided by exclusive access to valuable discovery space. The Keck Interferometer used its unique sensitivity to measure the dynamical masses of pre-main-sequence stars (Boden *et al.*, 2005; Schaefer *et al.*, 2008) — objects poorly treated by stellar models, in need of observational constraints — made the first extragalactic LBI observations, of AGN NGC4151 nucleus (Swain *et al.*, 2003), and probed the properties of faint T Tauri disks (Eisner *et al.*, 2005; Pott *et al.*, 2010). Larger scale surveys of AGN have proceeded with VLTI mid-IR observations (Jaffe *et al.*, 2004; Tristram *et al.*, 2009). Work done at the CHARA Array includes detection of discrepancies between theory and observation for low mass stars (Berger *et al.*, 2006), a comprehensive multiplicity survey (Raghavan *et al.*, 2010), and a series of papers empirically establishing the fundamental values of radius and temperature for main sequence stars (Boyajian *et al.*, 2012a,b, 2013); each of these studies have far-reaching implications throughout stellar astrophysics.

Instruments that are capable of combining many telescopes and measuring closure phases like MIRC (Monnier *et al.*, 2012) at CHARA and AMBER (Mérand *et al.*, 2010) at VLTI, have made imaging at milliarcsecond (mas) scales routine — for example rotationally distorted, oblate stellar photospheres (Monnier *et al.*, 2007; Zhao *et al.*, 2009; Che *et al.*, 2011); the eclipsing and interacting binary β Lyrae (Zhao *et al.*, 2008); high spectral

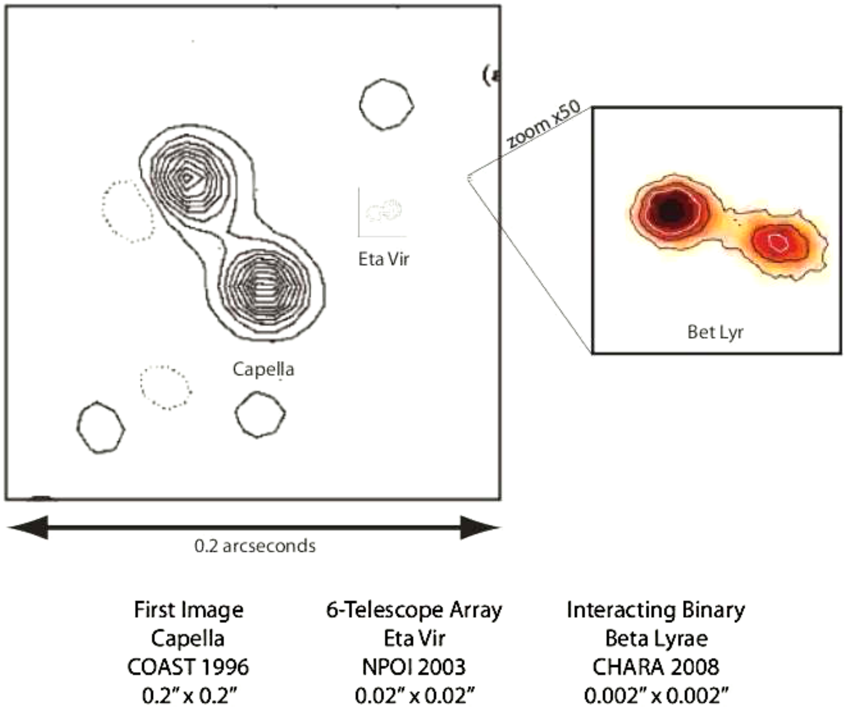

Fig. 1. This figure illustrates the profound improvement in imaging resolution over the last 12 years. The image on the left is the binary Capella with a separation of 0.05 arcsec and was the first object to be imaged by a long-baseline interferometer (Baldwin *et al.*, 1996). In the middle, shown with the same scale, is an image made using more telescopes and longer baselines of the inner component of Eta Virginis with a separation 0.006 arcsec (Hummel *et al.*, 2003). On the right, with the scale 100 times smaller, is a recent image of Beta Lyrae with a separation 0.8 mas, the first interacting binary ever to be resolved (Zhao *et al.*, 2008).

resolution images of the dynamical atmosphere of the red supergiant Antares (Ohnaka *et al.*, 2013); and the occultation of ϵ Aurigae (Kloppenborg *et al.*, 2010). CHARA and NPOI both confirmed Vega as a pole-on rapid rotator (Aufdenberg *et al.*, 2006; Peterson *et al.*, 2006), with remarkable implications for its status as a fundamental photometric calibrator, and for the irradiation of its debris disk.

2.1. *The CHARA/NPOI meeting*

Since 2005 the CHARA group has held annual group meetings. These meetings included all users of the instrument as well as all the groups who were building instruments for the Array. The content consists of a roughly 50/50 mix of instrument and science talks.(a) The intention has always been to be as inclusive as possible and other interferometry groups around the world have been invited to attend and present their most recent scientific results and instrument development. At the invitation of NPOI and the Lowell Observatory, this meeting was expanded in 2013 to become the first joint CHARA/NPOI science meeting and was hosted by the Lowell Observatory in Flagstaff. The meeting was held in conjunction with an Interferometry Forum, discussed below, and included representatives of all major interferometry groups around the world, including CHARA, NPOI, LBTI, VLTI, SUSI and MROI, and it is hoped that it will continue to expand in scope.

Since these meetings are necessarily rather informal and designed to promote open discussion of current issues in instrumentation development, it has not been our practice to produce written proceedings, however this most recent meeting was large enough to draw the attention of the Journal of Astronomical Instrumentation, who approached us with the idea of producing a special edition on Interferometry resulting in this very issue of the journal. Every attempt has been made to be as broad and inclusive as possible, and a majority of the papers herein are not even based on presentations at the CHARA/NPOI meeting. So, far from being a proceedings of a particular conference, we hope that

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[a] The presentations of all CHARA meetings can be found on the CHARA webpages at www.chara.gsu.edu.

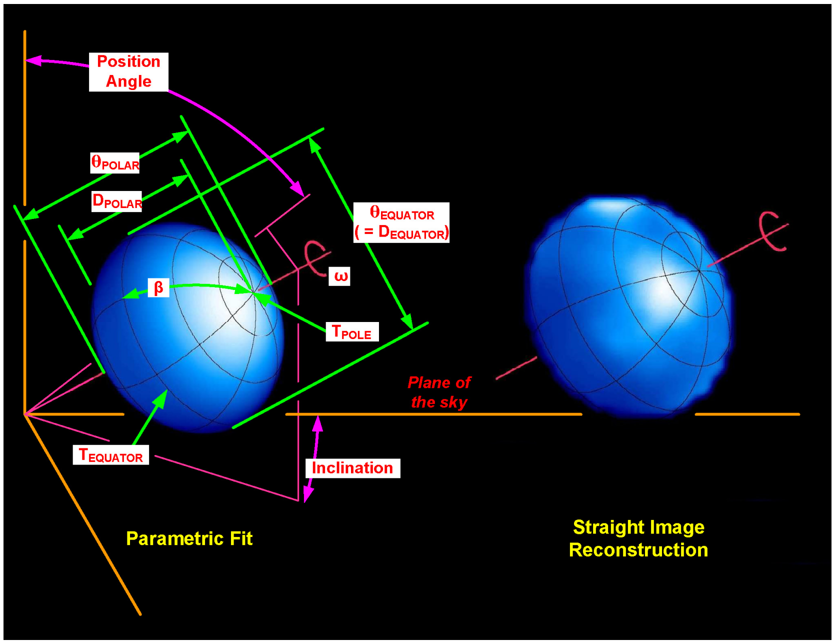

Fig. 2. A demonstration of the dramatic increase in detail for stellar characterization afforded by modern optical interferometry, from data on Altair collected with CHARA-MIRC (Monnier *et al.*, 2007, image credit: Ming Zhao). With a parametric fit (left), constrained as a rapidly rotating Roche model, values for multiple parameters can be recovered: equatorial angular diameter ($\theta_{\rm EQUATOR}$) and linear diameter ($D_{\rm EQUATOR}$); polar angular diameter ($\theta_{\rm POLE}$) and linear diameter ($D_{\rm POLE}$); effective temperatures at the equator ($T_{\rm EQUATOR}$) and pole ($T_{\rm POLE}$), along with the gravity darkening coefficient (β); viewing parameters such as object position angle upon the sky and inclination towards observer line-of-sight are also recovered. Separately, with the same data, a full image reconstruction can also be carried out (right), which provides an independent check on the underlying assumptions incorporated into the parametric fit.

this issue is a broader reflection of the current state of instrumentation in the field of ground based optical and near infrared Interferometry.

3. The Future

"Interferometry is inevitable," as famously quoted by Stephen Reinhart — a sentiment that sums up two converging streams in astronomy. First, continuing development and refinement of optical interferometry is making it a mainstream technique, obviating the need to be a 'black belt' in the technique to get anything useful from it. No technique in astronomy — e.g. spectroscopy or photometry — is simply point-and-shoot-and-publish, but the ever-increased polish on the user experience with optical interferometry is opening the umbrella to cover the needs and skills of more and more users.

The astronomy community has a nearly insatiable appetite for increased performance on two fronts: spatial resolution and sensitivity. It is on this first front that hinges the inevitability of interferometry: even the largest of the proposed next-generation filled apertures does not begin to match the angular resolution of the current optical arrays. High angular resolution is where the next great science discoveries are to be made: from the physics of last-time-of-light material falling into black holes, to mapping the continents of nearby exoplanets. Angular resolution requirements will only be satisfied by optical interferometry.

Like so many other types of Astronomy, going into space has many advantages for interferometry, not least the possibility of baselines much larger than can be accommodated on the surface of the earth. Indeed, a space based interferometer, albeit a small one, has been used for many years in the form of the Hubble Space Telescope Fine Guidance System, for example McNamara *et al.*, 2007. Space based interferometers have been proposed for direct planet detection (Martin *et al.*, 2011; Cockell *et al.*, 2009), astrometry (Coughlin *et al.*, 2010), and more recently for the detection of gravitational waves (Danzmann & Rüdiger, 2002). In the longer term, more general purpose astronomical facilities will make imaging of objects from stars to deep-field cosmology possible using baselines of thousands of kilometers (Labeyrie *et al.*, 2009).

3.1. *The interferometry forum*

What is the Next Big Thing? A number of options present themselves to the community: "plus-plus" upgrades to CHARA, NPOI, VLTI; full implementation of partially built facilities such as MROI; a major new start of a clean-sheet 'Optical VLA' could also be a possibility. In the end, this will be dictated by the intersection of three general strictures: what we in the optical interferometry community know we can build, what the general astronomy community want in terms of performance, and what is affordable.

Answering the first, and by extension, the last, of these strictures as an international community, has led to the establishment of the Interferometry Forum. The Forum is envisioned as an ongoing series of discussions to coordinate between the various groups and individuals interested in the technique of optical interferometry. The organization of the Forum is carried out under the auspices of the IAU Commission 54; C54 does not direct the discussion but aims to facilitate it, providing an opportunity for all to contribute to any formalized effort that will spring from these discussions. Two main organizations that are participating in these discussions are the European Interferometry Initiative (EII) and the US Interferometry Commission (USIC).(b)

The first of these meetings was hosted by Lowell Observatory in March of 2013, adjacent to the aforementioned CHARA/NPOI science meeting. A written report of the proceedings — both a comprehensive writeup, and an abbreviated executive summary — has been published online.(c) During the recent September 2013 "Interferometry Performances" colloquium at Observatoire de Haute-Provence, a second Forum-like international discussion was held, following the European interferometry special sessions (SP3, SP7) at the June 2013 EWASS meeting in Turku, Finland. An upcoming Interferometry Forum is being planned to be held adjacent to the 2014 June SPIE Montreal meeting.

Overall, there is a gathering momentum behind building an international consensus on answering that question of 'the Next Big Thing.' The mere existence of the Forum highlights the fact that the interferometry community recognizes that the technique has come of age in a compelling way, offering singularly unique access to fundamental discovery space.

4. Conclusion

It is in this context that this special issue of the Journal of Astronomical Instrumentation came to be. Many of the papers herein can be considered part of a proceedings from the CHARA/NPOI meeting in March of 2013, while many more are from research groups who did not attend that meeting. While this issue grew out of a particular set of meetings, every effort has been made to be as inclusive as possible, and every group working in the field were approached and asked to contribute. We hope that this issue will prove useful to those interested in the field and that it will not be the last of its kind sponsored by this journal.

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[b] Or, as time progresses, more likely the US-based successor to USIC. USIC was formed with a specific focus on the concerns of the optical interferometry community for the 2010 US Decadal Review.

[c] Available on the IAU Commission 54 Wiki: http://iauc54.wikispaces.com/2013+Interferometry+Forum.

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