Recent technical and scientific highlights from the CHARA Array

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ABSTRACT

The Center for High Angular Resolution Astronomy (CHARA) Array is a six-element interferometer with baselines ranging from 34 to 331 m. Three new beam combiners are entering operation: MYSTIC is a 6-telescope combiner for K-band; SPICA is a 6-telescope combiner for the visible R-band; and SILMARIL is a 3-telescope combiner for high sensitivity in H and K-bands. A seventh, portable telescope will use fiber optics for beam transport and will increase the baselines to 1 km. Observing time is available through a program funded by NSF. The programs are solicited and peer-reviewed by NSF's National Optical-Infrared Astronomy Research Laboratory. The open community access has significantly expanded the range of astronomical investigations of stars and their environments. Here we summarize the scientific work and the on-going technical advances of the CHARA Array.

Keywords: Interferometry, adaptive optics, CHARA Array

1. INTRODUCTION

The CHARA Array is a long baseline interferometer designed as a general facility for high angular resolution observations in the visible and near-infrared bands. It consists of six 1 m telescopes at fixed locations along three arms that are arranged around the historic telescopes of the Mount Wilson Observatory in the San Gabriel National Monument in southern California (Fig. 1). These telescopes act together to achieve the highest angular resolution available today (approximately 0.2 milliarcsec at a wavelength of 650 nm), and the Array is used in a wide range of astronomical studies that often include imaging applications. The Array achieved "first fringe" on its shortest and longest baselines in 1999 and 2001, respectively, and since then it has become a reliable, versatile, and productive facility for pioneering astrophysical research and instrumentation development.

The CHARA Array's six telescopes are arranged in a Y-shaped configuration yielding 15 interferometric baselines from 34 to 331 meters as well as 10 independent closure phases. The main components are described in full by ten Brummelaar et al. (2005).[1] These include the six light collecting telescopes (Fig. 1), telescope adaptive optics (TAO) benches attached to each mount, evacuated light pipes that direct the beams to a central facility (Fig. 1), an Optical Path Length Equalization (OPLE) laboratory with both fixed and variable delay, laboratory adaptive optics (LABAO) systems to correct for non-common path differences between beams, a beam switchyard, and a Beam Combining Laboratory (BCL) that houses a number of beam combiners for different wavelength bands and spectral dispersion (see Section 4). All these systems are controlled remotely and synchronously from a separate control room that has a high speed internet connection, and the observing program can be directed by astronomers anywhere in the world through a connection to a virtual remote operations computer located at the Georgia State University (GSU) campus in Atlanta.

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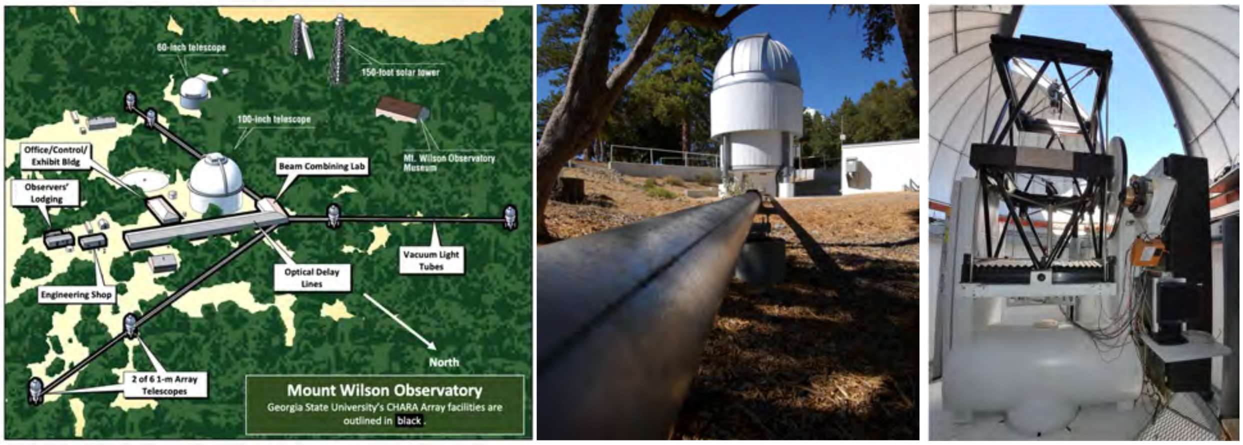

Figure 1: *Left:* Layout of the six CHARA telescopes at Mount Wilson. *Middle:* Dome and light pipe. *Right:* Telescope with the adaptive optics module in the black box on the right side.

The CHARA Array is owned by Georgia State University and operated through a site use agreement with the Mount Wilson Institute on behalf of the Carnegie Observatories. The project has grown over the years through the participation of many partners who have brought new expertise and instrumentation to the Array. The CHARA Consortium consists of groups (and their PIs) from University of Michigan (John Monnier), University of Exeter (Stefan Kraus), l'Observatoire de la Côte d'Azur (Denis Mourard), Université de Limoges (François Reynaud), l'Observatoire de Paris (Vincent Coudé du Foresto), University of Sydney (Peter Tuthill), Australian National University (Michael Ireland), Kyoto Sangyo University (Makoto Kishimoto), and the National Optical-Infrared Astronomy Research Laboratory (NOIRLab; Stephen Ridgway). The CHARA Array is maintained and developed by a staff of 16 individuals at Mount Wilson Observatory, and administrative and data archiving activities are managed at the GSU campus in Atlanta.

Observing time is available to faculty, students, and scientists associated with GSU and the CHARA Consortium, and also (since 2017) to the general community thanks to the support of the U.S. National Science Foundation. There are 80 nights per year reserved for the open access program that are divided between semesters A (March to July) and B (August to December). Observing time proposals are solicited and peer-reviewed through the NOIRLab application process, and the top-ranked programs are scheduled and enabled by CHARA staff. Interest in the open access program has grown, and the ratio of requested to awarded time has been around two in recent semesters. More than 300 unique scientists have used CHARA-related data in their investigations.

The CHARA Array is currently experiencing a remarkable burst of activity on both the instrumentational and observational sides, and this report is a summary of the work accomplished, underway, and planned for the future. Section 2 describes a diverse and rich set of scientific achievements from the CHARA Array that have appeared since the last SPIE report.[2] Sections 3 and 4 discuss recent improvements in infrastructure and the installation of new beam combiners, respectively. Several new initiatives to expand capability are outlined in Section 5. There were a number of major transitions in staff over the last year that are described in Section 6. We conclude with the outlook for the Array over the near and far terms in Section 7.

2. SCIENTIFIC RESULTS

Diameters of Stars – The CHARA Array provides the means to measure stellar angular diameters in all kinds of stars. Combining the diameter and distance yields the physical radius, and using the bolometric flux from the spectral energy distribution yields the effective temperature. Karovicova et al. (2022a)[3] and Karovicova et al. (2022b)[4] made a survey of a group of nine dwarfs and seven giant stars, respectively, to determine their fundamental properties and to serve as benchmark stars for large surveys. They use similar methods to find the parameters and metallicities of a set of metal-poor stars.[5,6] Gordon et al. (2018)[7] used CHARA/PAVO to measure angular diameters for six O-type stars, and Gordon et al. (2019)[8] extended the sample to 25 B-type stars. The diameters are consistent with expectations from model fits of the spectral energy distribution, but the temperatures derived from angular diameters and fluxes are about 4% larger than those based on analysis of the line spectrum. Schaefer et al. (2018)[9] used CHARA to observe 13 adolescent-age stars in nearby moving groups. None were found to host binary companions, and three were angularly resolved. The fundamental parameters derived from their diameters were used to estimate ages and test if the ages and other properties are consistent with membership in the AB Dor young moving group.

Direct measurements of angular diameters provide important tests of surface brightness-color relations that can be used to estimate diameters of stars that are too distant to resolve. Relations based upon CHARA interferometry and optical and near-IR color indices for a sample of main-sequence and evolved stars of A-K spectral types were determined by Adams, Boyajian, & von Braun (2018).[10] Salsi et al. (2021)[11] presented measurements with the VEGA combiner at CHARA of 18 early-type stars and used these to refine the surface brightness-color relation with application to a Gaia-spacecraft color index. The surface brightness-color relations depend on both spectral type (temperature) and luminosity class (gravity) in cooler stars, and Nardetto et al. (2020)[12] determined the relations for red giants while Salsi et al. (2020)[13] explored the relations over a range of luminosity classes for cool stars.

Angular diameters are particularly important for understanding the properties of unusual classes of stars. For example, Perraut et al. (2020)[14] derived fundamental parameters for a set of 14 chemically peculiar Ap stars. Another group of Ap stars is the focus of a study by Deal et al. (2021)[15] who used CHARA angular diameters and asteroseismology results to fit for the bulk chemistry and other stellar parameters. Their results indicate that the masses of Ap stars are systemically larger than found in previous studies. Romanovskaya et al. (2019)[16] determined that the radii of Ap stars found from careful spectroscopic analysis agree within errors with direct measurements from CHARA.

Sub-stellar brown dwarfs are expected to fade over time, so that their properties depend mainly on mass and age. Although it is difficult to determine both parameters in individual brown dwarfs, it is possible to determine ages of those with stellar companions by the positions of the stellar components with respect to evolutionary tracks in the HRD. Wood et al. (2019)[17] used CHARA observations of stellar primary components of HD 4747 and HD 19467 to determine their radii, temperatures, and luminosities. The derived ages are about 10 Gyr in each case, and current models predict much lower luminosities than observed for the brown dwarf components, an unexplained discrepancy.

Exoplanet Systems - Measurements of exoplanet host stars provide valuable insight about their habitable zones and other properties. Tayar et al. (2022)[18] explored the current limits on fundamental stellar properties from interferometric and spectrophotometric measurements for the characterization of solar-type exoplanet host stars. The issue of planet formation around intermediate mass stars can be explored through studies of their descendants, the subgiant stars. White et al. (2018)[19] obtained CHARA/PAVO observations of five evolved, intermediate-mass, planet-hosting stars, and determined their fundamental parameters and ages.

Analysis of transiting exoplanet light curves yields the ratio of planet to stellar radius, so a determination of the stellar radius from interferometry leads to the planetary radius. Ligi et al. (2019)[20] used CHARA/VEGA observations of HD 219134 to determine the radii of its two super-Earth exoplanets. Ellis et al. (2021)[21] made CHARA Array observations of the transiting, super-Earth host HD 97658 and measured its limb-darkened angular diameter to find the associated star and planet properties. A particularly special target is the exoplanet host star 55 Cnc that hosts five planets including 55 Cnc e, a transiting planet closest to the star. Crida et al. (2018)[22] analyzed the density and gaseous envelope of this super-Earth planet through a careful statistical investigation of the relation between the stellar and planetary parameters (the former from CHARA/VEGA measurements).

The F6 V star HD 113337 is the host of one confirmed and one candidate giant planet and a partially resolved debris disk. Borgniet et al. (2019)[23] used CHARA/VEGA measurements to determine the star's temperature and radius in order to determine its evolutionary state and age. They find two possible age solutions and determine estimates for the exoplanet masses. The exoplanet host star GJ 504A was the subject of a multi-faceted investigation by Bonnefoy et al. (2018).[24] They used CHARA/VEGA to measure the radius of the host star and to estimate its age from evolutionary tracks. The age is a clue to determining if the companion that appears in imaging is a brown dwarf or massive planet.

Imaging Starspots - We can explore the magnetic activity of stars by mapping the starspots that appear in their photospheres. CHARA MIRC observations by Parks et al. (2021)[25] show how the surface starspot distribution on the magnetically active star λ Andromedae changes over timescales of years. Martinez et al. (2021)[26] developed a new method of dynamical surface imaging to study the spot distributions and motions on the surface of the RS CVn star λ Andromedae (Fig. 2). Their work confirms earlier results indicating that the starspots appear to be confined to specific ranges of active latitudes.

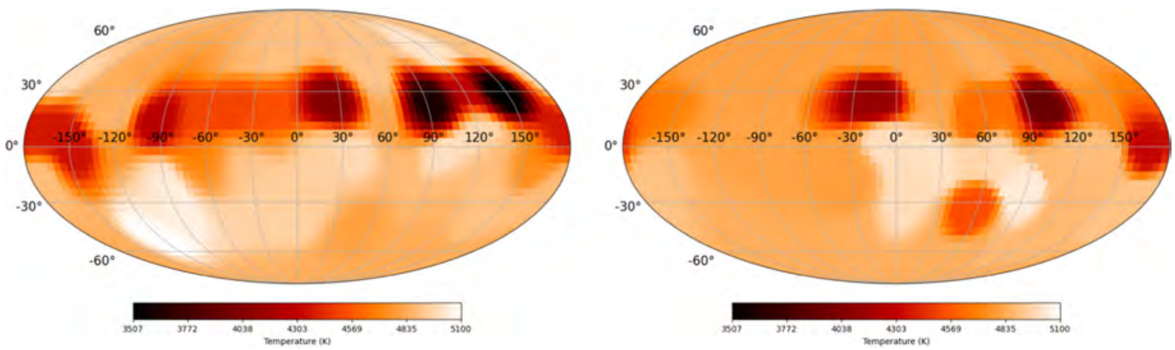

Figure 2: Temperature plots of starspots on the surface of λ Andromedae from the 2010 (left) and 2011 (right) observations from Martinez et al. (2021).[26]

Starspot maps hold the promise of providing the information needed to evaluate the radial velocity jitter caused by starspots and to correct the velocities in the search for Earth-like exoplanets. Roettenbacher et al. (2022)[27] conducted a pilot study using the CHARA Array and MIRC-X beam combiner to image directly the starspots detected in the TESS photometry. Their work indicates that future dedicated observing campaigns will provide the means to reduce significantly the radial velocity scatter.

Convection in Red Supergiants - Norris et al. (2021)[28] made maps of the convection cell features on the red supergiant AZ Cyg (Fig. 3). Their observations span a five year interval in which to explore the short- and long-term evolution of the surface features. The results indicate the presence of some large scale cells with characteristic size of about half the radius, similar to that found in numerical simulations. Small bright features appear to vary on a timescale less than one year, while larger features persist much longer.

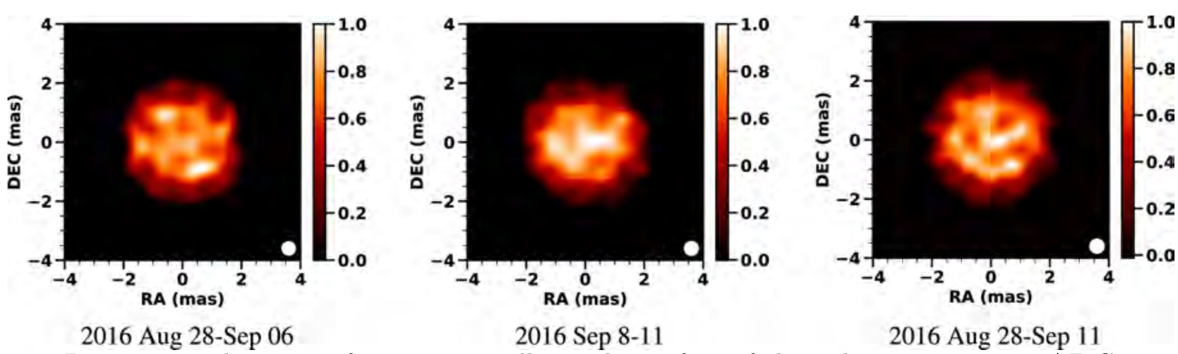

Figure 3: Reconstructed images of convection cells on the surface of the red supergiant star AZ Cyg in 2016 using data from August 28 – September 6, September 8 – 11, and entirety of the 2016 observations (from left to right) from Norris et al. (2021).[28]

Convection cells in Asymptotic Giant Branch (AGB) stars are large and bright enough to create astrometric, photocenter shifts that are measured with Gaia. Chiavassa et al. (2020)[29] created images of the AGB star CL Lac from MIRC-X observations, and these display bright patches that agree with expectations from 3D radiative hydrodynamics simulations of stellar convection and the observed astrometric jitter.

Pulsating Stars - Trahin et al. (2021)[30] developed the parallax-of-pulsation method through an algorithm called spectro-photo-interferometry of pulsating stars (SPIPS), which combines multi-band and multi-color photometry, radial velocity, effective temperature, and interferometry measurements to obtain Cepheid fundamental parameters. These are used to help refine calibrations of the period-luminosity and period-radius relations and to explore the dispersion of the projection factor relating the true and measured pulsation velocities. Gallenne et al. (2019)[31] continued their search for the B-star companions of Cepheid pulsators using CHARA/MIRC and VLTI/PIONIER. Their paper presents detections of companions in three Cepheids, with possible detections in six other cases. Follow up measurements to measure the orbits will provide the masses and distances for these Cepheids and will form a fundamental basis to check on the Cepheid period - luminosity ($P - L$) relation. For example, the binary Cepheid V1334 Cygni provides an anchor point with 1% distance accuracy for the $P - L$ relation.[32]

Asteroseismology of solar-like stars offers the means to estimate the primary stellar properties from the oscillation frequencies. Stokholm et al. (2019)[33] made an important test of the predictions through an interferometric and spectroscopic study of the subgiant HR 7322, a solar-like oscillator observed with a high cadence light curve from the NASA Kepler mission. There is good agreement between estimates of the star's radius from asteroseismology and interferometry, and comparisons with model predictions indicate that the interior has a smaller mixing length than found in the case of the Sun.

Disks Around Young Stars - Davies et al. (2020)[34] used CHARA observations plus lower angular resolution observations from other interferometers to study the near-IR emission from the disk surrounding the young star, RY Tau. They show that while the star itself is obscured by the disk, the stellar flux illuminates the inner edge of the disk beyond the star. The radius of the disk inner boundary is consistent with the position expected for the sublimation of silicate grains in the disk. The disk of the low mass, young stellar object, SU Aurigae, was explored through CHARA/CLIMB observations by Labdon et al. (2019).[35] They used new radiative transfer methods to fit the interferometric results, and they found that a vertically extended flux source is present that corresponds to a dusty wind originating near the inner boundary of the disk. This tends to confirm earlier work by Davies et al. (2018)[36] who found that observations of the Herbig Ae star, HD 142666, are best fit with models with an extended disk scale height.

The MWC 614 system has an inner gap in its disk that may be caused by clearing by a nascent planet. Kluska et al. (2018)[37] led a multiple-instrument program to map the disk geometry and search for a planet within the gap. They find evidence of extended near-IR emission (from CHARA and VLTI observations) within the gap region that may result from stellar heating of small dust particles. The Herbig Be star MWC 147 is an example of young systems that apparently have gaseous disks within the sublimation radius of the larger dust-dominated disk. Hone et al. (2019)[38] combined observations from VLTI and CHARA to show that this star has a K-band flux source that is as compact as that of the Brγ emission line, and this demonstrates the presence of hot gas within the gap between the star and the dust inner boundary.

Davies et al. (2022)[39] combined observations from the Gemini Planet Imager images with VLTI and CHARA near-IR interferometry to image and study the dust distribution in the disk surrounding the the young Herbig Ae star, HD 145718. The dust properties and disk orientation can cause variable obscuration of the star that is observed in dimming events. Setterholm et al. (2018)[40] examined the dust disks in two other Herbig Ae stars, HD 163296 and HD 190073. Both show evidence of significant emission near the radius of the predicted dust evaporation front, but the emission is more extended than expected for a sharp boundary. Labdon et al. (2021)[41] observed FU Ori, the prototype of YSOs that experience rapid brightening events due to enhanced disk accretion. They combined J and H-band imaging from MIRC-X to determine how the temperature declines with increasing disk radius from a near-stellar temperature close to the star-disk boundary.

Young multiple stars will experience tidal pulls that can dramatically influence the geometry of planet-forming disks. An instructive example is the young triple system GW Orionis. Kraus et al. (2020)[42] recorded the inner and outer orbital motions of GW Orionis using interferometric observations from VLTI and CHARA, and their results show the circumbinary disk experiences disk tearing and the formation of a misaligned, elliptical ring (Fig. 4).

The extended flux of debris disks around main sequence stars is found through diluted visibility curves in near-IR interferometry from CHARA and elsewhere. A study by Kirchschlager et al. (2018)[43] shows how the exozodi signal from hot dust increases with longer wavelength (M-band) in three specific examples.

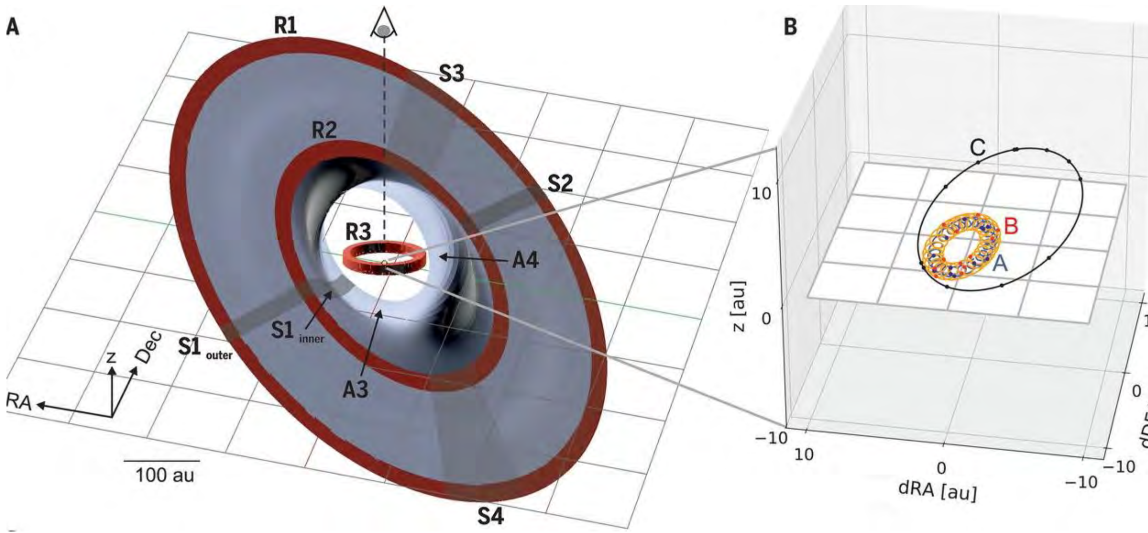

Figure 4: Geometry of the triple system GW Orionis and the torn accretion disk that surrounds the system (from Kraus et al. 2020[42]).

Outflows from Massive Stars - B-emission line stars are rapid rotators that are ejecting mass into a surrounding disk. The properties of such an outflowing disk are generally well-described by the Viscous Decretion Disk model in which the disk is relatively thin and the disk gas follows Keplerian orbits. De Almeida et al. (2020)[44] obtained interferometry from CHARA/VEGA and VLTI/AMBER of the Be star o Aquarii to study the disk dynamics through high spectral resolution of the Hα and Brγ emission lines. The Doppler shifts of the disk gas are close to those expected for Keplerian motion, and both lines suggest an outer emitting radius of 10 – 12 times the stellar radius ($4.0R_{\odot}$). This is a surprising result, because the larger optical depth of the Hα line usually causes its emitting region to be larger than that of Brγ. The discrepancy is examined in the context of radiative transfer models from the HDUST code.

Binary and Multiple Stars - The Array is ideal for direct resolution of close spectroscopic binaries, and combined angular and spectroscopic orbits yield the orbit, masses, and distance. Lester et al. (2019a, 2019b, 2020)[45–47] present orbits and masses for intermediate mass binaries that are far enough apart to have evolved as single stars (Fig. 5), and they determine the positions in the HRD for direct comparison with model evolutionary tracks for the derived masses. In most cases, there is gratifying agreement and the derived distances are the same within errors with the Gaia distances. This provides an important verification of consistency of the end-to-end measurement/analysis processes for both methods.

The intermediate mass binary system δ Del is a key test case for astrometric precision orbits. Gardner et al. (2018)[48] made careful measurements of the orbital motion using both the MIRC and PAVO beam combiners, and the residuals from the relative orbital fit are of order 10 microarcsec. They use the angular orbit together with a spectroscopic orbit based upon new Doppler shift measurements to derive the masses and distance. Analysis of the two spectral components yields the temperatures, and the fluxes and distance provide estimates of the radii. The placement of the stars in the HRD shows an unexplained difference in the estimated ages of the two components. Gardner et al. (2021)[49] used MIRC-X to make a new precise orbit for Rasalhague, a nearby rapidly rotating A5 IV star. This enabled a detailed comparison of the masses and the influence of rotation on the evolutionary tracks and observational properties.

Binary orbits provide a stable reference frame to search for astrometric wobbles introduced by low mass companions orbiting one of the components. Gardner et al. (2021)[50] are using the MIRC-X beam combiner with a careful calibration and analysis to measure astrometric wobbles approaching the 10 microarcsec level. Their paper announces the discovery of stellar companions in the (now triple) systems α Del and ν Gem (Fig. 6).

ν Gem is a remarkable triple system comprised of three $3M_{\odot}$ stars with an inner binary period of 54 days and an outer triple period of 19 years. The wider system is resolved in CHARA observations by Klement et al.

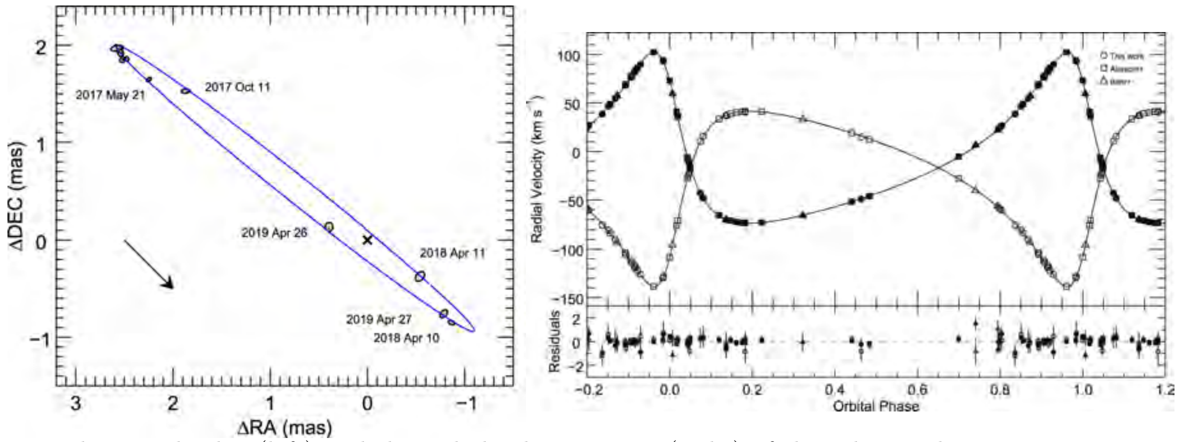

Figure 5: The visual orbit (left) and the radial velocity curve (right) of the eclipsing binary system HD 185912 from Lester et al. (2019b).[46]

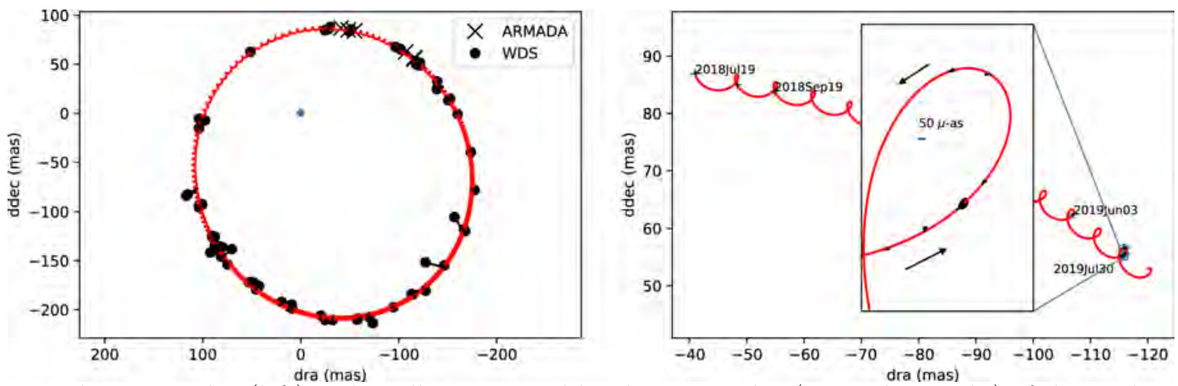

Figure 6: The outer orbit (left) and oscillation caused by the inner orbit (zoomed in, right) of the triple system α Del from the work of Gardner et al. (2021).[50]

(2021),[51] and their combined spectroscopic and interferometric analysis indicates that the tertiary is a rapidly rotating, Be-type emission line star. There is growing evidence that many of the emission-line Be stars were spun up by mass transfer in an interacting binary. The mass donor star is stripped of its envelope to become a hot but faint He star. Klement et al. (2022)[52] recently detected these binary companions and mapped their orbits with MIRC-X for several Be stars, opening the way to determining their orbital properties and masses.

The massive Wolf-Rayet stars have strong stellar winds that can dramatically reduce the star's mass over its lifetime. A combined interferometric and spectroscopic study of the WR+O binary system WR 140 by Thomas et al. (2021)[53] derived masses of 10 and $29 M_\odot$, respectively. The relatively low mass of the WR star is probably the result of wind mass loss alone without the need for binary mass transfer. The same team finds similar results in an investigation of the WR+O binary WR 133 (9 and $23 M_\odot$, respectively; Richardson et al. 2021[54]).

CHARA Array observations help to probe the mass transfer and gas dynamical processes in interacting binaries. Mourard et al. (2018)[55] examined the accretion disk around the mass gainer star in the famous close binary, β Lyrae, and they combined results from interferometry, multi-color light curves, and spectroscopy to develop an analytical model of the accretion disk. A detailed physical model was developed by Brož et al. (2021).[56] These models show how the thick accretion disk effectively blocks the flux from the mass gainer star.

Widely separated binaries (greater than 10 milliarcsec) can be measured using the separated fringe packet method. Farrington et al. (2018)[57] used this technique in a long-term observing program on the binary system HR 7345 with the difficult orbital period of 332 days (almost one year). They combined the CHARA visible orbit with a detailed spectroscopic orbit to determine the orbital elements and masses. This system has a very large eccentricity, $e = 0.93$, perhaps driven by a dynamical interaction with a third star.

3. TECHNICAL DEVELOPMENTS AT THE CHARA ARRAY

Telescope drives – The altitude and azimuth drive motors have served over two decades and are approaching the end of their useful operation. The current NSF grant includes funding to replace the existing Parker DM1015B-115 motors and their drives located on each of the six telescopes. There are two of these discontinued and 25 year old drives per telescope. Replacement of these drives will improve telescope performance and tuning of the system, leading to less variation with temperature and fewer vibrations.

The drive housings will be modified to fit the newer Parker motors while retaining the original Dojen reduction gearboxes and friction drive wheels (Fig. 7). The first replacement drive and motor for this project have been received. Software is currently being developed to integrate this drive into our system. The design of the physical mount for the new motor, which has a significantly different size and form from the present model, has been completed. Once the initial mount is fabricated, there will be a period of testing, after which the remaining drives, motors, and mount assemblies will be installed.

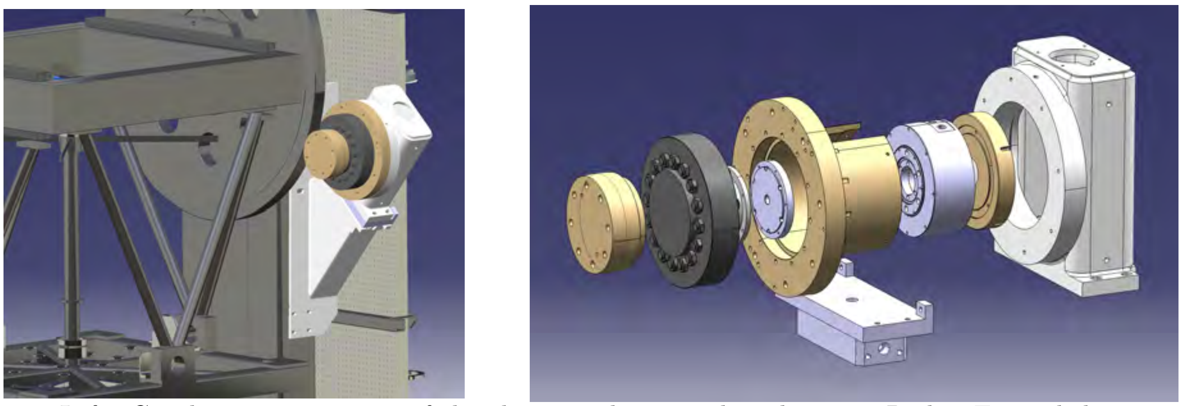

Figure 7: Left: Graphic representation of the elevation drive on the telescope. Right: Expanded view of the drive components.

Adaptive optics – The adaptive optics (AO) systems at CHARA are comprised of two AO subsystems for each telescope. The telescope AO (TAO) compensates for atmospheric turbulence and static aberrations in the telescope optics. Inside the beam pathlength compensation lab, a second AO (LABAO) subsystem corrects for aberrations introduced by the numerous reflective surfaces between the telescope and the beam combination laboratory as well as for atmospheric turbulence inside the beam path compensation lab.[58]

The six LABAO systems have been fully operational for several years and have served double duty as an excellent tool used to align the Array daily. The LABAO systems rely on 37 actuator, micro-machined membrane, deformable mirrors (DMs) built by OKO[*] controlled by Shack-Hartmann wavefront sensors (WFS) utilizing light ($\lambda = 450$ nm) injected into the path of the telescope beam at the telescope.[59]

Five TAO systems are fully operational with DMs installed (Fig. 8). The sixth system is currently operating as a tip-tilt detector and seeing monitor while its DM undergoes final calibration on our laboratory AO testbench. The TAO relies on a large custom 60 actuator DM built by ALPAO[†]. Replacing the fourth mirror in the optical train, the DM is held at 45 degrees and corrects the 125 mm beam from the telescope. Utilizing light reflected off one of three beam splitters, each with coatings reflecting different wavelengths, the DM is controlled by a WFS with an Andor[‡] EMCCD camera.[60]

In closed-loop operation, the TAO systems provide a diffraction limited beam to CHARA's near-infrared beam combiners and provide a full magnitude of sensitivity improvement to the Array. There are two current areas where work is ongoing to improve the AO system. First, efforts are being made to improve AO performance at visible wavelengths to improve beam quality for the new visible instrument SPICA. Second, improvements

[*]www.okothech.com

[†]www.alpao.com

[‡]www.andor.oxinst.com

are being developed for the calibration system for the TAO to facilitate near-automatic calibration of the DMs and reconstructor measurements on a nightly basis.

Delay line control system – The original control system for the moving delay line carts was in need of renewal due to the discontinuation of most of its electronic and computer components. We have replaced the original, JPL-built delay line control system with a system designed and built by Arizona Embedded Systems (AZESys[§]). The new system features a modular design using off-the-shelf components wherever possible and several custom-built embedded system components for high speed requirements. The embedded systems take full advantage of the advances in programmable logic chips and can be easily reprogrammed. We reused the stepper motor drivers, voice coil amplifiers, PZT controllers, and laser metrology system from the JPL-built system and interfaced them to the new control computers and embedded systems (Fig. 8). We hired a local programmer who worked closely with AZESys to create the layer of software which allows the new control system to seamlessly integrate with the existing CHARA Array control system, taking the same commands and returning the same telemetry as the JPL-built system. The new system is operational and working effectively.

Figure 8: Left: The upper part of one of the AO benches with the DM at top and WFS at lower right. Right: The computer rack that controls two of the delay lines. At the very top are the 1U embedded system components which deal with the metrology signals. The black 4U components are the Linux computers which link the delay line control hardware with the rest of the CHARA Array control system. The two sets of two 1U embedded system components between the two computers are the voice coil interface (the upper set), and the stepper motor supervisor and limit switch interface (the lower set). Below the two components with the large red buttons are the reused components described in the text.

Dispersion correction – Correction for both atmospheric and differential longitudinal dispersion can be a serious problem in ground-based interferometry especially in the visible wavelengths. The former can be corrected using standard techniques like the use of Risley prisms at the telescope, while the latter is largely alleviated by employing vacuum light transport systems as much as possible. Even with these vacuum light pipes, some residual differential longitudinal dispersion remains as the telescopes at CHARA are not at the same elevation and our movable delay lines are in open-air. This residual dispersion issue can be corrected by placing glass wedges

[§]http://www.azesys.com

in each beam that allow us to insert different amounts of glass to correct for the dispersion.[61] Unfortunately during the initial construction of the CHARA Array in the late 1990s, there was insufficient funding available to install longitudinal dispersion correctors (LDC) or the atmospheric dispersion correctors (ADC). Since our initial scientific observations were planned to be performed in the near-infrared H and K-bands, this was not a serious issue. However, towards the end of construction phase, resources were found to purchase the glass and necessary opto-mechanical instrumentation to implement a basic LDC system.[62,63] This was used with the visible beam combiner PAVO that was installed in the early 2000s.[64] This system worked well and was the main work-horse for dispersion correction at CHARA until late in 2020.

These original LDCs had two main issues. First, they were designed for correction in the visible only, and while they could be used in the near-IR as well, they introduced nearly a full magnitude loss in near-IR sensitivity. Second, with the addition of more sophisticated beam combiners like MIRC-X and MYSTIC in the near-IR and SPICA in the visible band (Section 4), it became clear that a new solution was necessary. This is particularly important, because we plan to observe with all three combiners in the V, R, I, J, H, and K-bands simultaneously.

In conjunction with the SILMARIL beam combiner project (Section 4), we were able to purchase new glass for the existing LDC system that was more transparent in the near-IR. These were installed in late 2020 and are now in regular use for both the visible and the near-IR. Furthermore, as part of the SPICA installation, a second set of LDC units were installed in the visible beams only. This dual LDC system, with one set of wedges common to both the near-IR and the visible and a second set of wedges in the visible light beams only, allows us to correct fully for longitudinal dispersion across all science wave-bands at the same time.[65] The SPICA beam combiner also includes ADC units for each of the six visible beams. Furthermore, the updated system adds small path length offsets in each beam combiner to account for the two different glasses in the two main optical bands.

4. BEAM COMBINERS

The suite of available and forthcoming beam combiners appears in Table 1. Notes follow on the newest of these combiners.

Table 1: CHARA Array Beam Combiners

Mode	Telescopes	Band	Typical Limiting Mag.	Best Performance Mag.	Spectral Resolution	Science Drivers
Acquisition, AO, Tip-tilt tracking	6	V-R band	10	12		
CLASSIC	2	H or K band	7.0	8.5	Broad band	Diameters
CLIMB	3	H or K band	6.0	7.0	Broad band	Binaries, Disks
SILMARIL*	3	H or K band	11	12	Broad band	AGN
MIRC-X	6	H-PRISM50	6.5	7.5	50	Imaging, Binaries, Disks
		H-GRISM190	5.5	6.5	190	
MYSTIC	4,6	K-PRISM49	6.5	7.5	49	Imaging, Binaries, Disks
PAVO	2	630-900 nm	7.0	8.0	30	Diameters
SPICA*	6	600-860 nm			200,4000,13000	Surveys

* Available 2023.

MIRC-X – The most frequently used beam combiner at present is the Michigan InfraRed Combiner-eXeter (MIRC-X) instrument built by Stefan Kraus and John Monnier[66] and described by Anugu et al. (2020).[67] This is a six-telescope interferometric imager for use in the J and H-band wavelengths. Fringes are recorded on a sensitive C-RED One camera based on an SAPHIRA detector.[68] MIRC-X provides excellent sensitivity, wavelength coverage into the J-band, and enables polarization observations.

MYSTIC – A companion instrument called the *Michigan Young STar Imager at CHARA* (MYSTIC) was constructed by John Monnier and installed in 2021.[69] This is 4- or 6-telescope combiner that is used in parallel with MIRC-X for simultaneous observing across the near-infrared bands. MYSTIC uses cold optics in a dewar to make sensitive observations in the K-band with a C-RED One ultra low-noise detector. Both MIRC-X and MYSTIC are designed for exploring disks surrounding YSOs and the conditions surrounding planet formation.

SPICA – Denis Mourard built a replacement for the VEGA visible band combiner that is called the *Stellar Parameters and Images with a Cophased Array* (SPICA).[70] This is a 6-telescope combiner for survey work in the visible that has several spectral dispersions. It uses single mode optical fibers to inject light into a spectrograph. SPICA employs a second-stage tip-tilt system to optimize flux input into the fibers and uses MIRC-X as a fringe tracker to permit longer exposures. SPICA is now in the testing and implementation phase at CHARA. A proto-type instrument for the SPICA visual-band combiner was built to test methods of fiber injection and adaptive optics control. The Fibered spectrally Resolved Interferometer - New Design (FRIEND) is based on single mode fibers and a Electron Multiplying Charge-Coupled Device (EMCCD) detector.[71] The instrument confirmed the basic design of injecting light into fibers mounted on a V-groove plate in a non-redundant pattern, and it was used to measure the diameters and separation of the massive binary ζ Ori A.

SILMARIL – SILMARIL is a new image-plane combiner being designed and constructed by Theo ten Brummelaar, Cyprien Lanthermann, and Peter Tuthill. The goal is to build a beam combiner specifically designed to optimize sensitivity. It will be limited to one of two independent sets of three telescope beams in order to minimize beam dilution. The design uses an edge filter to observe in the H and K-bands simultaneously. It will use low spectral resolution, allowing for group delay fringe tracking while maximizing the SNR of the fringes for each spectral channel. SILMARIL should extend observations to targets as faint as magnitude 12 in the H and K-bands. This new instrument should be ready for routine use in 2023.

5. FUTURE PLANS

The U.S. community recently completed the ASTRO2020 decadal review of important new programs in astrophysics.[72] There were 12 Science White Papers that were submitted in advance of the survey that emphasized the key role of interferometry in astrophysics. In addition, there were four White Papers submitted on Activities, Projects, or State of the Profession Consideration, and these included future plans for CHARA, NPOI, and MROI. We presented the outline of a plan for the CHARA Michelson Array,[73] a new interferometer for the next decades that builds on the strengths of the CHARA Array. We envision an array of twelve 2 m aperture telescopes at Mount Wilson that convey light beams by fiber optics to the central beam combining facility. The new array would have longest baselines in excess of a kilometer and would be designed for imaging applications. The current combination laboratory would be expanded but would rely on much of the current infrastructure and suite of beam combiners.

The first step to this goal is a project called the CHARA Michelson Array Pathfinder (CMAP) that is being led by Robert Ligon. We will add a portable 1 m aperture telescope to the Array that will be stationed at three or four sites on Mount Wilson. The new baselines would expand the spatial dynamic range of the CHARA Array by creating baselines as small as 10 m (in a triangle with telescopes S1 and S2) and as large as 1.1 km (for very high angular resolution). Light beams from the mobile and existing telescopes will be relayed by fiber optic cables for initial operation in the H-band. The 1 m PW1000 telescope has been ordered from PlaneWave Instruments[¶], and experiments in fiber control are underway using a set of polarization maintaining fibers from the original ‘OHANA project.[74] The CMAP instrument will be ready for on-sky experiments in 2024.

Work on fiber optics at CHARA has already begun by François Reynaud who is leading an experiment called the *Astronomical Light Optical Hybrid Analysis* (ALOHA) program.[75] The idea is to mix the near-infrared light from a star with a laser reference and use non-linear optics to up-convert the output signal to the sum of the frequencies. The result is a signal in the visible band that can be recorded with conventional detectors. The focus now is to up-convert L-band flux at 3.5 μm to a visible band wavelength of 817 nm. Magri et al. (2021)[76] discuss the input-stage optics for ALOHA and use laboratory tests to estimate a limiting magnitude of $L = 3.9$ mag for use with the CHARA Array 1 m telescopes. The current experiment uses two optical fibers of 200 m in length to direct the light to the combiner in the laboratory. Lehmann et al. (2019)[77] discuss methods used to control and stabilize the optical path difference between the fibers.

[¶]https://planewave.com

6. STAFF TRANSITIONS

The success of the CHARA Array is due to the outstanding efforts of a devoted and talented staff. Over the past year, a number of the original CHARA team members have retired after careers of remarkable accomplishment. These include Laszlo Sturmann (Chief Systems Scientist), Judit Sturmann (Optical Systems Scientist), Larry Webster (Site Manager), and Theo ten Brummelaar (Director of the CHARA Array; Fig. 9). Theo was an outstanding leader in the work of the CHARA Array interferometer. Theo started at GSU as a postdoctoral associate in 1993. Once construction of the Array began, Theo moved to California to help lead the project from the site. He was promoted to Research Scientist in 1996, became Associate Director in 2001, and then Director of the Array in 2015 upon Professor Hal McAlister's retirement. Under Theo's leadership the Array has grown in capability and efficiency, and the Array is now serving the research needs of scientists from around the globe.

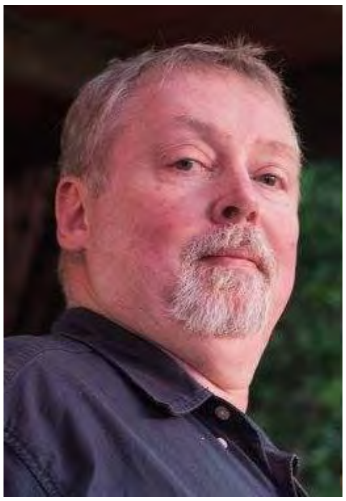
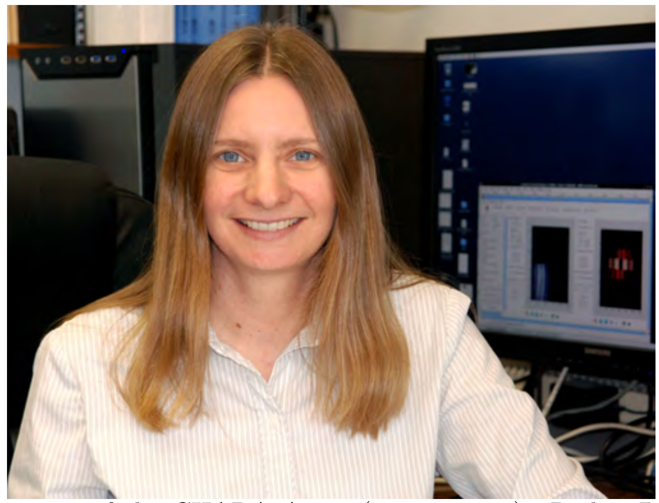

Figure 9: Left: Dr. Theo ten Brummelaar, Director of the CHARA Array (2015 – 2022). Right: Dr. Gail Schaefer, current Director of the CHARA Array.

The new Director of the CHARA Array is Dr. Gail Schaefer (Fig. 9). Gail joined the GSU CHARA staff in 2007, and she has worked at Mount Wilson Observatory ever since. She has been involved in all facets of the Array operations including leading the support of the open access program. Gail now leads a staff that includes new staff members Nicholas Scott, Narsireddy Anugu, and Robert Ligon, plus new postdoctoral associates Matthew Anderson, Cyprien Lanthermann, and Rainer Köhler and new Assistant Site Manager Victor Castillo. The entire staff is dedicated to advancing the scientific mission of the Array.

7. CONCLUSIONS

The CHARA Array is now in its eighteenth year of operation, and the pace of its current scientific and instrumental activity is greater than ever. There are now some 226 papers in the peer-reviewed literature based upon CHARA data‖, and thanks to the NSF-sponsored open access program, the community of users is growing with each observing semester. The suite of beam combiners of MIRC-X, MYSTIC, and SPICA will soon enable simultaneous observations in all bands and with all telescopes as the standard observing mode at the CHARA Array. The introduction of the highly sensitive, three-telescope combiner SILMARIL will bring a host of fainter targets into accessibility, including several dozen Active Galactic Nuclei. The CMAP mobile telescope program will greatly enlarge the spatial dynamic range of the Array, and this will provide imaging opportunities of large red supergiants (at short baselines) and diameter measurements of distant hotter stars (at long baselines). The CMAP program will also demonstrate how fiber optic transport can open the way to much longer baselines in future interferometers. The CHARA Array will continue its mission to promote the methods and means to explore the high angular resolution universe.

‖https://www.chara.gsu.edu/astronomers/journal-articles

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REFERENCES

[1] ten Brummelaar, T. A., McAlister, H. A., Ridgway, S. T., Bagnuolo, W. G., J., Turner, N. H., Sturmann, L., Sturmann, J., Berger, D. H., Ogden, C. E., Cadman, R., Hartkopf, W. I., Hopper, C. H., and Shure, M. A., "First Results from the CHARA Array. II. A Description of the Instrument," ApJ **628**, 453–465 (July 2005).

[2] Gies, D. R., ten Brummelaar, T. A., Anderson, M. D., Farrington, C. D., Golden, S., Jones, J. W., Klement, R., Majoinen, O., Schaefer, G. H., Sturmann, J., Sturmann, L., Turner, N. H., Vargas, N. L., Webster, L., Woods, C., and Ridgway, S. T., "Recent technical and scientific highlights from the CHARA array," in *Optical and Infrared Interferometry and Imaging VI*, Creech-Eakman, M. J., Tuthill, P. G., and M érand, A., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10701**, 1070102 (July 2018).

[3] Karovicova, I., White, T. R., Nordlander, T., Casagrande, L., Ireland, M., and Huber, D., "Fundamental stellar parameters of benchmark stars from CHARA interferometry. II. Dwarf stars," A&A **658**, A47 (Feb. 2022a).

[4] Karovicova, I., White, T. R., Nordlander, T., Casagrande, L., Ireland, M., and Huber, D., "Fundamental stellar parameters of benchmark stars from CHARA interferometry. III. Giant and subgiant stars," A&A **658**, A48 (Feb. 2022b).

[5] Karovicova, I., White, T. R., Nordlander, T., Lind, K., Casagrande, L., Ireland, M. J., Huber, D., Creevey, O., Mourard, D., Schaefer, G. H., Gilmore, G., Chiavassa, A., Wittkowski, M., Jofré, P., Heiter, U., Thévenin, F., and Asplund, M., "Accurate effective temperatures of the metal-poor benchmark stars HD 140283, HD 122563, and HD 103095 from CHARA interferometry," MNRAS **475**, L81–L85 (Mar. 2018).

[6] Karovicova, I., White, T. R., Nordlander, T., Casagrande, L., Ireland, M., Huber, D., and Jofré, P., "Fundamental stellar parameters of benchmark stars from CHARA interferometry. I. Metal-poor stars," A&A **640**, A25 (Aug. 2020).

[7] Gordon, K. D., Gies, D. R., Schaefer, G. H., Huber, D., Ireland, M., and Hillier, D. J., "Angular Sizes and Effective Temperatures of O-type Stars from Optical Interferometry with the CHARA Array," ApJ **869**, 37 (Dec. 2018).

[8] Gordon, K. D., Gies, D. R., Schaefer, G. H., Huber, D., and Ireland, M., "Angular Sizes, Radii, and Effective Temperatures of B-type Stars from Optical Interferometry with the CHARA Array," ApJ **873**, 91 (Mar. 2019).

[9] Schaefer, G. H., White, R. J., Baines, E. K., Boyajian, T. S., ten Brummelaar, T. A., Farrington, C. D., Sturmann, J., Sturmann, L., and Turner, N. H., "AB Dor Moving Group Stars Resolved with the CHARA Array," ApJ **858**, 71 (May 2018).

[10] Adams, A. D., Boyajian, T. S., and von Braun, K., "Predicting stellar angular diameters from V, I_C, H and K photometry," MNRAS **473**, 3608–3614 (Jan. 2018).

[11] Salsi, A., Nardetto, N., Mourard, D., Graczyk, D., Taormina, M., Creevey, O., Hocdé, V., Morand, F., Perraut, K., Pietrzynski, G., and Schaefer, G. H., "Progress on the calibration of surface brightness-color relations for early- and late-type stars," A&A **652**, A26 (Aug. 2021).

[12] Nardetto, N., Salsi, A., Mourard, D., Hocdé, V., Perraut, K., Gallenne, A., Mérand, A., Graczyk, D., Pietrzynski, G., Gieren, W., Kervella, P., Ligi, R., Meilland, A., Morand, F., Stee, P., Tallon-Bosc, I., and ten Brummelaar, T., "Calibrating the surface brightness - color relation for late-type red giants stars in the visible domain using VEGA/CHARA interferometric observations," A&A **639**, A67 (July 2020).

[13] Salsi, A., Nardetto, N., Mourard, D., Creevey, O., Huber, D., White, T. R., Hocdé, V., Morand, F., Tallon-Bosc, I., Farrington, C. D., Chelli, A., and Duvert, G., "Precise calibration of the dependence of surface brightness-colour relations on colour and class for late-type stars," A&A **640**, A2 (Aug. 2020).

[14] Perraut, K., Cunha, M., Romanovskaya, A., Shulyak, D., Ryabchikova, T., Hocdé, V., Nardetto, N., Mourard, D., Meilland, A., Morand, F., Tallon-Bosc, I., Farrington, C., and Lanthermann, C., "Benchmarking the fundamental parameters of Ap stars with optical long-baseline interferometric measurements," A&A **642**, A101 (Oct. 2020).

[15] Deal, M., Cunha, M. S., Keszthelyi, Z., Perraut, K., and Holdsworth, D. L., "Fundamental properties of a selected sample of Ap stars: Inferences from interferometric and asteroseismic constraints," A&A **650**, A125 (June 2021).

[16] Romanovskaya, A., Ryabchikova, T., Shulyak, D., Perraut, K., Valyavin, G., Burlakova, T., and Galazutdinov, G., "Fundamental parameters and evolutionary status of the magnetic chemically peculiar stars HD 188041 (V1291 Aquilae), HD 111133 (EP Virginis), and HD 204411: spectroscopy versus interferometry," MNRAS **488**, 2343–2356 (Sept. 2019).

[17] Wood, C. M., Boyajian, T., von Braun, K., Brewer, J. M., Crepp, J. R., Schaefer, G., Adams, A., and White, T. R., "Benchmarking Substellar Evolutionary Models Using New Age Estimates for HD 4747 B and HD 19467 B," ApJ **873**, 83 (Mar. 2019).

[18] Tayar, J., Claytor, Z. R., Huber, D., and van Saders, J., "A Guide to Realistic Uncertainties on the Fundamental Properties of Solar-type Exoplanet Host Stars," ApJ **927**, 31 (Mar. 2022).

[19] White, T. R., Huber, D., Mann, A. W., Casagrande, L., Grunblatt, S. K., Justesen, A. B., Silva Aguirre, V., Bedding, T. R., Ireland, M. J., Schaefer, G. H., and Tuthill, P. G., "Interferometric diameters of five evolved intermediate-mass planet-hosting stars measured with PAVO at the CHARA Array," MNRAS **477**, 4403–4413 (July 2018).

[20] Ligi, R., Dorn, C., Crida, A., Lebreton, Y., Creevey, O., Borsa, F., Mourard, D., Nardetto, N., Tallon-Bosc, I., Morand, F., and Poretti, E., "From the stellar properties of HD 219134 to the internal compositions of its transiting exoplanets," A&A **631**, A92 (Nov. 2019).

[21] Ellis, T. G., Boyajian, T., von Braun, K., Ligi, R., Mourard, D., Dragomir, D., Schaefer, G. H., and Farrington, C. D., "Directly Determined Properties of HD 97658 from Interferometric Observations," AJ **162**, 118 (Sept. 2021).

[22] Crida, A., Ligi, R., Dorn, C., and Lebreton, Y., "Mass, Radius, and Composition of the Transiting Planet 55 Cnc e: Using Interferometry and Correlations," ApJ **860**, 122 (June 2018).

[23] Borgniet, S., Perraut, K., Su, K., Bonnefoy, M., Delorme, P., Lagrange, A. M., Bailey, V., Buenzli, E., Defrère, D., Henning, T., Hinz, P., Leisenring, J., Meunier, N., Mourard, D., Nardetto, N., Skemer, A., and Spalding, E., "Constraints on HD 113337 fundamental parameters and planetary system. Combining long-base visible interferometry, disc imaging, and high-contrast imaging," A&A **627**, A44 (July 2019).

[24] Bonnefoy, M., Perraut, K., Lagrange, A. M., Delorme, P., Vigan, A., Line, M., Rodet, L., Ginski, C., Mourard, D., Marleau, G. D., Samland, M., Tremblin, P., Ligi, R., Cantalloube, F., Mollière, P., Charnay, B., Kuzuhara, M., Janson, M., Morley, C., Homeier, D., D'Orazi, V., Klahr, H., Mordasini, C., Lavie, B., Baudino, J. L., Beust, H., Peretti, S., Musso Bartucci, A., Mesa, D., Bézard, B., Boccaletti, A., Galicher, R., Hagelberg, J., Desidera, S., Biller, B., Maire, A. L., Allard, F., Borgniet, S., Lannier, J., Meunier, N., Desort, M., Alecian, E., Chauvin, G., Langlois, M., Henning, T., Mugnier, L., Mouillet, D., Gratton, R., Brandt, T., Mc Elwain, M., Beuzit, J. L., Tamura, M., Hori, Y., Brandner, W., Buenzli, E., Cheetham, A., Cudel, M., Feldt, M., Kasper, M., Keppler, M., Kopytova, T., Meyer, M., Perrot, C., Rouan, D., Salter, G., Schmidt, T., Sissa, E., Zurlo, A., Wildi, F., Blanchard, P., De Caprio, V., Delboulbé, A., Maurel, D., Moulin, T., Pavlov, A., Rabou, P., Ramos, J., Roelfsema, R., Rousset, G., Stadler, E., Rigal, F., and Weber, L., "The GJ 504 system revisited. Combining interferometric, radial velocity, and high contrast imaging data," A&A **618**, A63 (Oct. 2018).

[25] Parks, J. R., White, R. J., Baron, F., Monnier, J. D., Kloppenborg, B., Henry, G. W., Schaefer, G., Che, X., Pedretti, E., Thureau, N., Zhao, M., ten Brummelaar, T., McAlister, H., Ridgway, S. T., Turner, N., Sturmann, J., and Sturmann, L., "Interferometric Imaging of λ Andromedae: Evidence of Starspots and Rotation," ApJ **913**, 54 (May 2021).

[26] Martinez, A. O., Baron, F. R., Monnier, J. D., Roettenbacher, R. M., and Parks, J. R., "Dynamical Surface Imaging of λ Andromedae," ApJ **916**, 60 (July 2021).

[27] Roettenbacher, R. M., Cabot, S. H. C., Fischer, D. A., Monnier, J. D., Henry, G. W., Harmon, R. O., Korhonen, H., Brewer, J. M., Llama, J., Petersburg, R. R., Zhao, L. L., Kraus, S., Le Bouquin, J.-B., Anugu, N., Davies, C. L., Gardner, T., Lanthermann, C., Schaefer, G., Setterholm, B., Clark, C. A., Jorstad, S. G., Kuehn, K., and Levine, S., "EXPRES. III. Revealing the Stellar Activity Radial Velocity Signature of ϵ Eridani with Photometry and Interferometry," AJ **163**, 19 (Jan. 2022).

[28] Norris, R. P., Baron, F. R., Monnier, J. D., Paladini, C., Anderson, M. D., Martinez, A. O., Schaefer, G. H., Che, X., Chiavassa, A., Connelley, M. S., Farrington, C. D., Gies, D. R., Kiss, L. L., Lester, J. B., Montargès, M., Neilson, H. R., Majoinen, O., Pedretti, E., Ridgway, S. T., Roettenbacher, R. M., Scott, N. J., Sturmann, J., Sturmann, L., Thureau, N., Vargas, N., and ten Brummelaar, T. A., "Long Term Evolution of Surface Features on the Red Supergiant AZ Cyg," ApJ **919**, 124 (Oct. 2021).

[29] Chiavassa, A., Kravchenko, K., Millour, F., Schaefer, G., Schultheis, M., Freytag, B., Creevey, O., Hocdé, V., Morand, F., Ligi, R., Kraus, S., Monnier, J. D., Mourard, D., Nardetto, N., Anugu, N., Le Bouquin, J. B., Davies, C. L., Ennis, J., Gardner, T., Labdon, A., Lanthermann, C., Setterholm, B. R., and ten Brummelaar, T., "Optical interferometry and Gaia measurement uncertainties reveal the physics of asymptotic giant branch stars," A&A **640**, A23 (Aug. 2020).

[30] Trahin, B., Breuval, L., Kervella, P., Mérand, A., Nardetto, N., Gallenne, A., Hocdé, V., and Gieren, W., "Inspecting the Cepheid parallax of pulsation using Gaia EDR3 parallaxes. Projection factor and period-luminosity and period-radius relations," A&A **656**, A102 (Dec. 2021).

[31] Gallenne, A., Kervella, P., Borgniet, S., Mérand, A., Pietrzyński, G., Gieren, W., Monnier, J. D., Schaefer, G. H., Evans, N. R., Anderson, R. I., Baron, F., Roettenbacher, R. M., and Karczmarek, P., "Multiplicity of Galactic Cepheids from long-baseline interferometry. IV. New detected companions from MIRC and PIONIER observations," A&A **622**, A164 (Feb. 2019).

[32] Gallenne, A., Kervella, P., Evans, N. R., Proffitt, C. R., Monnier, J. D., Mérand, A., Nelan, E., Winston, E., Pietrzyński, G., Schaefer, G., Gieren, W., Anderson, R. I., Borgniet, S., Kraus, S., Roettenbacher, R. M., Baron, F., Pilecki, B., Taormina, M., Graczyk, D., Mowlavi, N., and Eyer, L., "A Geometrical 1% Distance to the Short-period Binary Cepheid V1334 Cygni," ApJ **867**, 121 (Nov. 2018).

[33] Stokholm, A., Nissen, P. E., Silva Aguirre, V., White, T. R., Lund, M. N., Mosumgaard, J. R., Huber, D., and Jessen-Hansen, J., "The subgiant HR 7322 as an asteroseismic benchmark star," MNRAS **489**, 928–940 (Oct. 2019).

[34] Davies, C. L., Kraus, S., Harries, T. J., Monnier, J. D., Kloppenborg, B., Aarnio, A., Baron, F., Lopez, R. G., Millan-Gabet, R., Parks, R., Pedretti, E., Perraut, K., Sturmann, J., Sturmann, L., ten Brummelaar, T. A., and Touhami, Y., "The Inner Disk of RY Tau: Evidence of Stellar Occultation by the Disk Atmosphere at the Sublimation Rim from K-band Continuum Interferometry," ApJ **897**, 31 (July 2020).

[35] Labdon, A., Kraus, S., Davies, C. L., Kreplin, A., Kluska, J., Harries, T. J., Monnier, J. D., ten Brummelaar, T., Baron, F., Millan-Gabet, R., Kloppenborg, B., Eisner, J., Sturmann, J., and Sturmann, L., "Dusty disk winds at the sublimation rim of the highly inclined, low mass young stellar object SU Aurigae," A&A **627**, A36 (July 2019).

[36] Davies, C. L., Kraus, S., Harries, T. J., Kreplin, A., Monnier, J. D., Labdon, A., Kloppenborg, B., Acreman, D. M., Baron, F., Millan-Gabet, R., Sturmann, J., Sturmann, L., and Ten Brummelaar, T. A., "Simultaneous Spectral Energy Distribution and Near-infrared Interferometry Modeling of HD 142666," ApJ **866**, 23 (Oct. 2018).

[37] Kluska, J., Kraus, S., Davies, C. L., Harries, T., Willson, M., Monnier, J. D., Aarnio, A., Baron, F., Millan-Gabet, R., Ten Brummelaar, T., Che, X., Hinkley, S., Preibisch, T., Sturmann, J., Sturmann, L., and Touhami, Y., "A Multi-instrument and Multi-wavelength High Angular Resolution Study of MWC 614: Quantum Heated Particles Inside the Disk Cavity," ApJ **855**, 44 (Mar. 2018).

[38] Hone, E., Kraus, S., Davies, C. L., Kreplin, A., Monnier, J. D., Baron, F., Millan-Gabet, R., Hofmann, K.-H., Schertl, D., Sturmann, J., Sturmann, L., Ten Brummelaar, T., and Weigelt, G., "Compact gaseous accretion disk in Keplerian rotation around MWC 147," A&A **623**, A38 (Mar. 2019).

[39] Davies, C. L., Rich, E. A., Harries, T. J., Monnier, J. D., Laws, A. S. E., Andrews, S. M., Bae, J., Wilner, D. J., Anugu, N., Ennis, J., Gardner, T., Kraus, S., Labdon, A., Le Bouquin, J.-B., Lanthermann, C., Schaefer, G. H., Setterholm, B. R., Ten Brummelaar, T., and G-Lights Collaboration, "Scattering and

sublimation: a multiscale view of μm-sized dust in the inclined disc of HD 145718," MNRAS **511**, 2434–2452 (Apr. 2022).

[40] Setterholm, B. R., Monnier, J. D., Davies, C. L., Kreplin, A., Kraus, S., Baron, F., Aarnio, A., Berger, J.-P., Calvet, N., Curé, M., Kanaan, S., Kloppenborg, B., Le Bouquin, J.-B., Millan-Gabet, R., Rubinstein, A. E., Sitko, M. L., Sturmann, J., ten Brummelaar, T. A., and Touhami, Y., "Probing the Inner Disk Emission of the Herbig Ae Stars HD 163296 and HD 190073," ApJ **869**, 164 (Dec. 2018).

[41] Labdon, A., Kraus, S., Davies, C. L., Kreplin, A., Monnier, J. D., Le Bouquin, J.-B., Anugu, N., ten Brummelaar, T., Setterholm, B., Gardner, T., Ennis, J., Lanthermann, C., Schaefer, G., and Laws, A., "Viscous heating in the disk of the outbursting star FU Orionis," A&A **646**, A102 (Feb. 2021).

[42] Kraus, S., Kreplin, A., Young, A. K., Bate, M. R., Monnier, J. D., Harries, T. J., Avenhaus, H., Kluska, J., Laws, A. S. E., Rich, E. A., Willson, M., Aarnio, A. N., Adams, F. C., Andrews, S. M., Anugu, N., Bae, J., ten Brummelaar, T., Calvet, N., Curé, M., Davies, C. L., Ennis, J., Espaillat, C., Gardner, T., Hartmann, L., Hinkley, S., Labdon, A., Lanthermann, C., Le Bouquin, J.-B., Schaefer, G. H., Setterholm, B. R., Wilner, D., and Zhu, Z., "A triple-star system with a misaligned and warped circumstellar disk shaped by disk tearing," *Science* **369**, 1233–1238 (Sept. 2020).

[43] Kirchschlager, F., Wolf, S., Brunngräber, R., Matter, A., Krivov, A. V., and Labdon, A., "Modelling of mid-infrared interferometric signature of hot exozodiacal dust emission," MNRAS **473**, 2633–2638 (Jan. 2018).

[44] de Almeida, E. S. G., Meilland, A., Domiciano de Souza, A., Stee, P., Mourard, D., Nardetto, N., Ligi, R., Tallon-Bosc, I., Faes, D. M., Carciofi, A. C., Bednarski, D., Mota, B. C., Turner, N., and ten Brummelaar, T. A., "Visible and near-infrared spectro-interferometric analysis of the edge-on Be star o Aquarii," A&A **636**, A110 (Apr. 2020).

[45] Lester, K. V., Gies, D. R., Schaefer, G. H., Farrington, C. D., Monnier, J. D., ten Brummelaar, T., Sturmann, J., and Vargas, N., "Visual Orbits of Spectroscopic Binaries with the CHARA Array. I. HD 224355," AJ **157**, 140 (Apr. 2019a).

[46] Lester, K. V., Gies, D. R., Schaefer, G. H., Farrington, C. D., Guo, Z., Matson, R. A., Monnier, J. D., ten Brummelaar, T., Sturmann, J., Vargas, N., and Weiss, S. A., "Visual Orbits of Spectroscopic Binaries with the CHARA Array. II. The Eclipsing Binary HD 185912," AJ **158**, 218 (Dec. 2019b).

[47] Lester, K. V., Fekel, F. C., Muterspaugh, M., Gies, D. R., Schaefer, G. H., Farrington, C. D., Guo, Z., Matson, R. A., Monnier, J. D., ten Brummelaar, T., Sturmann, J., and Weiss, S. A., "Visual Orbits of Spectroscopic Binaries with the CHARA Array. III. HD 8374 and HD 24546," AJ **160**, 58 (Aug. 2020).

[48] Gardner, T., Monnier, J. D., Fekel, F. C., Williamson, M., Duncan, D. K., White, T. R., Ireland, M., Adams, F. C., Barman, T., Baron, F., ten Brummelaar, T., Che, X., Huber, D., Kraus, S., Roettenbacher, R. M., Schaefer, G., Sturmann, J., Sturmann, L., Swihart, S. J., and Zhao, M., "Precision Orbit of δ Delphini and Prospects for Astrometric Detection of Exoplanets," ApJ **855**, 1 (Mar. 2018).

[49] Gardner, T., Monnier, J. D., Fekel, F. C., Williamson, M., Baron, F., Hinkley, S., Ireland, M., Kraus, A. L., Kraus, S., Roettenbacher, R. M., Schaefer, G., Sturmann, J., Sturmann, L., and ten Brummelaar, T., "Establishing α Oph as a Prototype Rotator: Precision Orbit with New Keck, CHARA, and RV Observations," ApJ **921**, 41 (Nov. 2021).

[50] Gardner, T., Monnier, J. D., Fekel, F. C., Schaefer, G., Johnson, K. J. C., Le Bouquin, J.-B., Kraus, S., Anugu, N., Setterholm, B. R., Labdon, A., Davies, C. L., Lanthermann, C., Ennis, J., Ireland, M., Kratter, K. M., Ten Brummelaar, T., Sturmann, J., Sturmann, L., Farrington, C., Gies, D. R., Klement, R., and Adams, F. C., "ARMADA. I. Triple Companions Detected in B-type Binaries α Del and ν Gem," AJ **161**, 40 (Jan. 2021).

[51] Klement, R., Hadrava, P., Rivinius, T., Baade, D., Cabezas, M., Heida, M., Schaefer, G. H., Gardner, T., Gies, D. R., Anugu, N., Lanthermann, C., Davies, C. L., Anderson, M. D., Monnier, J. D., Ennis, J., Labdon, A., Setterholm, B. R., Kraus, S., ten Brummelaar, T. A., and Le Bouquin, J.-B., "ν Gem: A Hierarchical Triple System with an Outer Be Star," ApJ **916**, 24 (July 2021).

[52] Klement, R., Schaefer, G. H., Gies, D. R., Wang, L., Baade, D., Rivinius, T., Gallenne, A., Carciofi, A. C., Monnier, J. D., Mérand, A., Anugu, N., Kraus, S., Davies, C. L., Lanthermann, C., Gardner, T., Wysocki, P., Ennis, J., Labdon, A., Setterholm, B. R., and Le Bouquin, J.-B., "Interferometric Detections of sdO Companions Orbiting Three Classical Be Stars," ApJ **926**, 213 (Feb. 2022).

[53] Thomas, J. D., Richardson, N. D., Eldridge, J. J., Schaefer, G. H., Monnier, J. D., Sana, H., Moffat, A. F. J., Williams, P., Corcoran, M. F., Stevens, I. R., Weigelt, G., Zainol, F. D., Anugu, N., Le Bouquin, J.-B., ten Brummelaar, T., Campos, F., Couperus, A., Davies, C. L., Ennis, J., Eversberg, T., Garde, O., Gardner, T., Fló, J. G., Kraus, S., Labdon, A., Lanthermann, C., Leadbeater, R., Lester, T., Maki, C., McBride, B., Ozuyar, D., Ribeiro, J., Setterholm, B., Stober, B., Wood, M., and Zurmühl, U., "The orbit and stellar masses of the archetype colliding-wind binary WR 140," MNRAS **504**, 5221–5230 (July 2021).

[54] Richardson, N. D., Lee, L., Schaefer, G., Shenar, T., Sander, A. A. C., Hill, G. M., Fullard, A. G., Monnier, J. D., Anugu, N., Davies, C. L., Gardner, T., Lanthermann, C., Kraus, S., and Setterholm, B. R., "The First Dynamical Mass Determination of a Nitrogen-rich Wolf-Rayet Star Using a Combined Visual and Spectroscopic Orbit," ApJ **908**, L3 (Feb. 2021).

[55] Mourard, D., Brož, M., Nemravová, J. A., Harmanec, P., Budaj, J., Baron, F., Monnier, J. D., Schaefer, G. H., Schmitt, H., Tallon-Bosc, I., Armstrong, J. T., Baines, E. K., Bonneau, D., Božić, H., Clausse, J. M., Farrington, C., Gies, D., Juryšek, J., Korčáková, D., McAlister, H., Meilland, A., Nardetto, N., Svoboda, P., Šlechta, M., Wolf, M., and Zasche, P., "Physical properties of β Lyrae A and its opaque accretion disk," A&A **618**, A112 (Oct. 2018).

[56] Brož, M., Mourard, D., Budaj, J., Harmanec, P., Schmitt, H., Tallon-Bosc, I., Bonneau, D., Božić, H., Gies, D., and Šlechta, M., "Optically thin circumstellar medium in the β Lyr A system," A&A **645**, A51 (Jan. 2021).

[57] Farrington, C. D., Fekel, F. C., Schaefer, G. H., and ten Brummelaar, T. A., "Separated Fringe Packet Observations with the CHARA Array. III. The Very High-eccentricity Binary HR 7345," AJ **156**, 144 (Oct. 2018).

[58] ten Brummelaar, T. A., Sturmann, J., Sturmann, L., Anderson, M. D., Turner, N. H., Ireland, M. J., Monnier, J. D., Mourard, D., Ridgway, S. T., Gies, D. R., and Le Bouquin, J.-B., "The CHARA Array adaptive optics program," in *Adaptive Optics Systems VI*, Close, L. M., Schreiber, L., and Schmidt, D., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10703**, 1070304 (July 2018).

[59] ten Brummelaar, T., Che, X., McAlister, H., Ireland, M., Monnier, J., Mourard, D., Ridgway, S., Sturmann, J., Sturmann, L., Turner, N., and Tuthill, P., "CHARA Array adaptive optics II: non-common-path correction and downstream optics," in *Adaptive Optics Systems IV*, Marchetti, E., Close, L. M., and Vran, J.-P., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9148**, 91484Q (Aug. 2014).

[60] Che, X., Sturmann, L., Monnier, J. D., ten Brummelaar, T. A., Sturmann, J., Ridgway, S. T., Ireland, M. J., Turner, N. H., and McAlister, H. A., "The CHARA Array adaptive optics I: common-path optical and mechanical design, and preliminary on-sky results," in *Adaptive Optics Systems IV*, Marchetti, E., Close, L. M., and Vran, J.-P., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9148**, 914830 (July 2014).

[61] ten Brummelaar, T. A., "Differential path considerations in optical stellar interferometry," Appl. Opt. **34**, 2214–2219 (May 1995).

[62] Berger, D. H., Bagnuolo, W. G., ten Brummelaar, T. A., and McAlister, H. A., "Longitudinal Dispersion Compensation for a Long Baseline Optical Interferometer," in *American Astronomical Society Meeting Abstracts*, *American Astronomical Society Meeting Abstracts* **203**, 24.02 (Dec. 2003).

[63] Berger, D. H., ten Brummelaar, T. A., Bagnuolo, William G., J., and McAlister, H. A., "Preliminary results from the longitudinal dispersion compensation system for the CHARA Array," in *Interferometry for Optical Astronomy II*, Traub, W. A., ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4838**, 974–982 (Feb. 2003).

[64] Ireland, M. J., Mérand, A., ten Brumme laar, T. A., Tuthill, P. G., Schaefer, G. H., Turner, N. s. H., Sturmann, J., Sturmann, L., and McAlister, H. A., "Sensitive visible interferometry with PAVO," in *Optical and Infrared Interferometry*, Schöller, M., Danchi, W. C., and Delplancke, F., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7013**, 701324 (July 2008).

[65] Pannetier, C., Mourard, D., Cassaing, F., Lagarde, S., Le Bouquin, J.-B., Monnier, J., Sturmann, J., and Ten Brummelaar, T., "Compensation of differential dispersion: application to multiband stellar interferometry," MNRAS **507**, 1369–1380 (Oct. 2021).

[66] Kraus, S., Monnier, J. D., Anugu, N., Le Bouquin, J.-B., Davies, C. L., Ennis, J., Labdon, A., Lanthermann, C., Setterholm, B., and ten Brummelaar, T., "The MIRC-X 6-telescope imager: key science drivers, instrument design and operation," in *Optical and Infrared Interferometry and Imaging VI*, Creech-Eakman, M. J., Tuthill, P. G., and Mérand, A., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10701**, 1070123 (July 2018).

[67] Anugu, N., Le Bouquin, J.-B., Monnier, J. D., Kraus, S., Setterholm, B. R., Labdon, A., Davies, C. L., Lanthermann, C., Gardner, T., Ennis, J., Johnson, K. J. C., Ten Brummelaar, T., Schaefer, G., and Sturmann, J., "MIRC-X: A Highly Sensitive Six-telescope Interferometric Imager at the CHARA Array," AJ **160**, 158 (Oct. 2020).

[68] Lanthermann, C., Anugu, N., Le Bouquin, J. B., Monnier, J. D., Kraus, S., and Perraut, K., "Modeling the e-APD SAPHIRA/C-RED One camera at low flux level. An attempt to count photons in the near-infrared with the MIRC-X interferometric combiner," A&A **625**, A38 (May 2019).

[69] Monnier, J. D., Le Bouquin, J.-B., Anugu, N., Kraus, S., Setterholm, B. R., Ennis, J., Lanthermann, C., Jocou, L., and ten Brummelaar, T., "MYSTIC: Michigan Young STar Imager at CHARA," in *Optical and Infrared Interferometry and Imaging VI*, Creech-Eakman, M. J., Tuthill, P. G., and Mérand, A., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10701**, 1070122 (July 2018).

[70] Mourard, D., Nardetto, N., ten Brummelaar, T., Bailet, C., Berio, P., Bresson, Y., Cassaing, F., Clausse, J.-M., Dejonghe, J., Lagarde, S., Martinod, M.-A., Michau, V., Perraut, K., Petit, C., Tallon, M., and Tallon-Bosc, I., "SPICA, a new 6T visible beam combiner for CHARA: science, design and interfaces," in *Optical and Infrared Interferometry and Imaging VI*, Creech-Eakman, M. J., Tuthill, P. G., and Mérand, A., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10701**, 1070120 (July 2018).

[71] Martinod, M. A., Mourard, D., Bério, P., Perraut, K., Meilland, A., Bailet, C., Bresson, Y., ten Brummelaar, T., Clausse, J. M., Dejonghe, J., Ireland, M., Millour, F., Monnier, J. D., Sturmann, J., Sturmann, L., and Tallon, M., "Fibered visible interferometry and adaptive optics: FRIEND at CHARA," A&A **618**, A153 (Oct. 2018).

[72] National Academies of Sciences, Engineering, and Medicine, "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," (2021).

[73] Gies, D., ten Brummelaar, T., Schaefer, G., Baron, F., and White, R., "The CHARA Michelson Array," in *Bulletin of the American Astronomical Society*, **51**, 226 (Sept. 2019).

[74] Woillez, J., Lai, O., Perrin, G., Reynaud, F., Baril, M., Dong, Y., and Fédou, P., "AGILIS: Agile Guided Interferometer for Longbaseline Imaging Synthesis. Demonstration and concepts of reconfigurable optical imaging interferometers," A&A **602**, A116 (June 2017).

[75] Reynaud, F., Darré, P., Szemendera, L., Gomes, J.-T., Grossard, L., and Delage, L., "ALOHA project: how nonlinear optics can boost interferometry to propose a new generation of instrument for high-resolution imaging," in *Optical and Infrared Interferometry and Imaging V*, Malbet, F., Creech-Eakman, M. J., and Tuthill, P. G., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9907**, 99071A (July 2016).

[76] Magri, J., Lehmann, L., Grossard, L., Delage, L., Reynaud, F., Chauvet, M., Bassignot, F., Krawczyk, R., and Le Duigou, J.-M., "Influence of the input-stage architecture on the in-laboratory test of a mid-infrared interferometer: application to the ALOHA up-conversion interferometer in the L band," MNRAS **501**, 531–540 (Feb. 2021).

[77] Lehmann, L., Delage, L., Grossard, L., Reynaud, F., Golden, S., Woods, C., Webster, L., Sturmann, J., and Brummelaar, T. t., "Environmental characterisation and stabilisation of a 2×200-meter outdoor fibre interferometer at the CHARA Array," *Experimental Astronomy* **47**, 303–312 (June 2019).