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Interferometry with Meter-Class Telescopes

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Abstract. Small telescopes have the potential to be connected into an interferometric array to effectively make a significantly larger telescope. Interferometric arrays utilizing small telescopes, particularly the Center for High-Angular Resolution Astronomy (CHARA) Array, are at the forefront of optical interferometry with observations leading to accurate stellar radii and even images of stellar surfaces. Here, the challenges and advantages of small-telescope, long-baseline optical interferometry will be discussed, alongside the current status and recent results from small-telescope interferometric arrays.

Key words: Instrumentation: interferometers – Techniques: interferometric – Stars: imaging

1. Introduction

Long-baseline optical interferometry (LBOI) is a technique that allows for a number of small telescopes to be connected to effectively make a much larger telescope. While individual telescopes are limited in angular resolution, θ, by the diffraction limit $\theta \approx \lambda/D$, where λ is wavelength and D is telescope diameter, the angular resolution of an interferometer is $\theta \approx \lambda/B$, where B is the distance between two telescopes (the baseline). This allows for smaller telescopes to be used together in order to obtain the resolution of a prohibitively large telescope with a single or segmented mirror.

Light emitted from a star at one point in time will hit the telescopes in an array at different times, traveling a different distance to each telescope. In order to make use of interference between the light collected at the different telescopes, the light emitted from the star at one point in time must be recombined at the same time. Unlike sub-millimeter and radio interferometry, LBOI, which operates in visible and infrared wavelengths, requires the light be combined at the interferometer. In order to account for the difference in path length that the light travels, there are movable delay lines that lengthen the distance that the light travels.

Each pair of telescopes used to make an observation is a projected baseline that uniquely maps to a point on the stellar surface (or one point in the uv plane, the projection of each baseline onto the plane of the sky). As the Earth rotates, the projected baseline of each pair of telescopes changes and different points on the stellar surface are mapped to. By observing a target for many hours or even nights, the surface can be mapped by the interferometric observations.

For more detailed explanations of optical interferometry, see Lawson (2000) and Labeyrie et al. (2006).

2. Long-baseline Optical Interferometers

Today, there are three routinely-functioning long-baseline optical interferometers. The interferometers are all different, and included here are the major characteristics of each. Also included is an interferometer currently being constructed and another being discussed as the next-generation interferometer.

2.1. Very Large Telescope Interferometer

The Very Large Telescope Interferometer (VLTI) is located at the European Southern Observatory (ESO; Paranal, Chile). The interferometer is capable of combining light from either the four 8.2-m Unit Telescopes (UTs) or four 1.8-m Auxiliary Telescopes (ATs). The baselines accessible to VLTI span lengths up to 130 m. While the locations of the UTs are fixed, the ATs are movable. The configurations of the ATs change several times each observing semester and are designed such that no two baselines are the same in a single configuration. Up to four telescopes can be combined at once at VLTI, allowing for 6 baselines for each configuration (Glindemann et al., 2000). Recently, the New Adaptive Optics Module for Interferometry (NAOMI) has been added to the ATs to improve performance (Le Bouquin et al., 2018).

Currently, three instruments are available at VLTI that each combine four telescopes and can be used on either the UTs or ATs. The Precision Integrated-Optics Near-infrared Imaging ExpeRiment (PIONIER) combines light in H-band (Le Bouquin et al., 2011). GRAVITY is combines light in K-band and can reach resolutions of 2 milliarcseconds (mas) with the longest baseline of the ATs (Gravity Collaboration et al., 2017). The Multi-AperTure mid-Infrared SpectrScopic Experiment (MATISSE) can be used in L, M, or N band, with $R \sim 1000$ in L-band (Lopez et al., 2014).

Up-to-date, detailed information can be found at `https://www.eso.org/sci/facilities/paranal/telescopes/vlti.html`.

2.2. Navy Precision Optical Interferometer

The Navy Precision Optical Interferometer (NPOI) is located at the Anderson Mesa Station of Lowell Observatory (Arizona, USA) and is jointly run by the U.S. Naval Observatory, the Naval Research Laboratory, and Lowell Observatory. Currently, NPOI consists of six siderostats that are located at fixed positions. However, three new movable 1-m telescopes are being obtained and installed. NPOI will have baselines spanning 8–432 m (van Belle et al., 2018).

There are three instruments available at NPOI. NPOI Classic combines light from two telescopes in visible wavelengths. New Classic is similar, but uses light from three telescopes (Sun et al., 2014). The Visible Imaging System for Interferometric Observations at NPOI (VISION) combines light from six telescopes in the visible wavelengths (Garcia et al., 2016, based off of the MIRC instrument at CHARA, see below) for a maximum resolution of ~ 0.2 mas.

Information on NPOI can be found at `http://www2.lowell.edu/rsch/npoi/index.php`.

2.3. Center for High-Angular Resolution Astronomy Array

The Center for High-Angular Resolution Astronomy (CHARA) Array is owned and operated by Georgia State University. The CHARA Array is located at Mount Wilson Observatory (California, USA). The CHARA Array consists of six 1-m telescopes at fix locations. The baselines span 34–331 m (ten Brummelaar et al., 2005). When using all six telescopes, 15 different baselines are possible. Currently, adaptive optics are being installed at each telescope to improve seeing and magnitude limits (ten Brummelaar et al., 2018).

The CHARA Array has six beam combiners available. The CLASSIC and the CLassic Interferometry with Multiple Baselines (CLIMB) beam combiners at the CHARA Array make use of two or three telescopes, respectively, and operate in H- or K-band (ten Brummelaar et al., 2013). The Jouvence of the Fiber-Linked Unit for optical recombination (JouFLU) beam combiner uses two telescopes and operates in the K-band (Scott et al., 2013). The two-beam Precision Astronomical Visible Observations (PAVO) instrument operates in visible wavelengths (Ireland et al., 2008). The Visible spEctroGraph and polArimeter (VEGA) beam combiner uses visible light from four telescopes and can operate with a resolution of to $R \sim 30000$. The Michigan InfraRed Combiner (MIRC) instrument was the first interferometric instrument able to combine light from six telescopes (Monnier et al., 2004). MIRC originally worked in H-band, but recent upgrades to MIRC-X allow for observations in H- and J-bands (Kraus et al., 2018), with maximum resolutions of 0.5 and 0.4 mas, respectively.

Current information can be found at `http://www.chara.gsu.edu/`.

2.4. Magdalena Ridge Observatory Interferometer

The Magdalena Ridge Observatory Interferometer (MROI) is currently under construction by the New Mexico Institute of Mining and Technology. It is located at Magdalena Ridge Observatory (New Mexico, US). When complete, MROI will consist of 10 1.4-m telescopes. There will be a total of 28 positions for the telescopes with baselines possible from 7.8–347 m.

The first telescope had first light in 2016 (Creech-Eakman et al., 2018). With the second telescope arriving by the end of 2019, first fringes are expected in 2020. Up-to-date information can be found at `http://www.mro.nmt.edu/about-mro/interferometer-mroi/`.

2.5. Planet Formation Imager

The Planet Formation Imager (PFI) is a concept for the next generation of interferometers. PFI will consist of twelve 3-m telescopes and have a maximum baseline of 1.2 km, a significant increase over current baseline sizes. This increase will allow for an angular resolution (~ 0.2 mas) capable of imaging planets in their protoplanetary disks (Monnier et al., 2018). Many of the current interferometric technologies need to be advanced to adapt to this significantly bigger and more complicated array.

For more information on PFI, see `http://www.planetformationimager.org/`.

3. Science Results

Using stellar interferometers to measure the angular diameter of stars were first theorized and attempted in the mid-nineteenth century, but it was nearly fifty years before the diameter of a star was first directly measured. The interferometers and instruments listed above are only the most recent and most impressive iterations capable of doing far more then measuring angular diameters, θ. With these tools, LBOI has been used to produce a wide range of results in astronomy, many of which have been fundamental to the field.

3.1. Stellar Radii

The first and most common results from interferometry are angular diameters (e.g., Michelson & Pease, 1921). Along with parallax estimates, this is a straight-forward measurement of the radius of a star. These observations have been collected for hundreds of stars in order to establish a well-constrained relationships between temperatures and radii across the Hertzsprung-Russell (H-R) diagram (e.g., Boyajian et al., 2015). Radii measurements of low-mass stars, in particular, have been used to improve theoretical interior and atmosphere models (e.g., Ségransan et al., 2003; Berger et al., 2006).

Using detailed measurements of stellar diameters, the ages of co-evolving stars can be constrained (e.g., Jones et al., 2015, for the Ursa Major moving group). Changes in angular diameter can be measured for pulsating stars, such as Cepheid variables (e.g., Mérand et al., 2005).

3.2. Binary Orbits and Stellar Multiplicity

Interferometry has been able to constrain the orbits of a number and large variety of binary systems using visual detections (e.g., Anderson, 1920). Combining interferometric and radial velocity observations allows for a detailed understanding of the system, resulting in the ability to determine stellar masses and place the system components on the H-R diagram (e.g., Roettenbacher et al., 2015b). Interferometry also makes it possible to detect the secondary components of single-lined spectroscopic orbits with the ability to detect secondary stars up to nearly 400 times fainter than the primary (the highest confirmed H-band flux ratio between primary and secondary components is 370:1 with MIRC at the CHARA Array; Roettenbacher et al., 2015a). The VLTI interferometric detection of nearby companions have been instrumental in showing that nearly all O-stars ($91 \pm 3\%$; Sana et al., 2014) are gravitationally bound to at least one other star.

Very recently, the orbits of stars at the center of the galaxy have been measured interferometrically (Gravity Collaboration et al., 2018) with the GRAVITY instrument and the UTs at VLTI. These remarkable observations serve as tests to general relativity.

3.3. Parametric Model Fitting and Aperture Synthesis Imaging

When combining observations from many baselines, parametric model fitting and aperture synthesis imaging become possible. Parametric model fitting uses regularization to obtain the best-fit model based on the information on the object's size, shape, orientation, etc. that is extracted from interferometric data. The aperture synthesis technique allows for the stars to be directly imaged as they appear on the sky. A distinct advantage of aperture synthesis is that imaging techniques using other types of observations (e.g., Doppler imaging with high-resolution spectroscopy) have degeneracies in the location of features on the stellar surface and are unable to determine the position angle on the sky.

Parametric model fitting has been used, in particular, to investigate the structure of disks around stars. For example, this includes young stellar objects, Herbig Ae/Be stars (e.g., Lazareff et al., 2017, with PIONIER at VLTI), disks around post-asymptotic giant branch binary systems (e.g., Hillen et al., 2017, with the decommissioned MID-infrared Interferometric (MIDI) combiner at VLTI), and Be star disks (e.g., ζ Tauri, Tycner et al., 2004, with NPOI).

The first image of a main-sequence star other the Sun was imaged using the MIRC beam combiner at the CHARA Array. With this technique, Altair was shown to definitively be an oblate spheroid from its rapid rotation (Monnier et al., 2007). Altair was just one of several rapidly rotating stars to be used to constrain gravity darkening in stars with radiative outer envelopes (e.g., Che et al., 2011; Zhao et al., 2011). The distorted shape of interacting binary systems has also been imaged (e.g., Zhao et al., 2008; Baron et al., 2012).

The disk of ejected material around the Be star δ Scorpii has been imaged throughout the star's orbit (Che et al., 2012). Another system with a disk, ϵ Aurigae was observed throughout the eclipse of the supergiant primary star by a companion with a disk. A series of interferometric images clearly show the disk passing in front of the supergiant star (Kloppenborg et al., 2010). The eject of Nova Delphini 2013 was observed interferometrically as it expanded. On three nights of observation, the expanding shell was imaged and showed signs of asymmetry (Schaefer et al., 2014).

Features on the surfaces of stars are also resolved. The temperature differences across convective cells of asymptotic giant branch stars have been resolved (Paladini et al., 2018). Snapshot images of cool stars with starspots have also been obtained (Hummel et al., 2017). The entire surface of the spotted stars ζ Andromedae and σ Geminorum have been imaged by observing with the MIRC instrument at the CHARA Array throughout a stellar rotation (Roettenbacher et al., 2016, 2017).

4. Summary

LBOI is a unique and powerful tool that allows us to obtain fundamental measurements and direct images of the stars. Current interferometers are used for a wide variety of science, from measuring stellar angular diameters to determining the orbit of stars at the galactic center to detecting spots on the stellar surface. The references for the science cases included here merely scratch the surface of the literature available on each topic. The upcoming advancements in interferometric instrumentation and technology will allow for studies across astronomy, particularly probes into stellar astrophysics and the formation of stellar and protoplanetary systems to detect the beginnings of planet formation.

The slides for the talk associated with these conference proceedings can be found at `https://www.astro.sk/conferences/75AI2018/talks/A02.pdf`.

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