PROJECT DESCRIPTION

INTRODUCTION – We request funding under the NSF ATI Program to develop and install small field of view low order natural guide star Adaptive Optics (AO) on the six telescopes of the CHARA Array - an interferometric facility producing milliarcsecond resolution images in the optical and near infrared. The benefits of AO to the CHARA Array are:

- More sensitivity - 1 to 5 magnitudes depending on the type of object and the seeing. This means more targets can be observed, including new classes of objects.
- Improved performance on bright targets - measurements with more precision and detection of lower contrast fringes produces higher dynamic range images.
- More consistent performance through varying seeing conditions. This will greatly improve our scientific throughput.

A low-order on-axis AO system of very small field of view is sufficient for our application and presents no new challenges to AO technology or design. We choose a design strategy that gives most of the achievable performance gain at moderate cost, with the result that the entire project can be carried out within the ATI program. A less expensive Phase I program, one that includes the detector systems and a static wavefront correction, is an option for funding at a lower level. This would provide all the benefits of improved tip/tilt performance, as well as wave front diagnosis, providing a substantial fraction of the science, as well as enabling the complete Phase II system for an alternative funding stream or for a future time.

The CHARA Array is located at Mount Wilson Observatory in the San Gabriel Mountains of Southern California. The Array utilizes the principles of optical and infrared interferometry to link its telescopes together to produce resolution equivalent to that of a single telescope more than 300 meters in diameter, giving it capabilities that are unsurpassed internationally. With 43 publications in the refereed literature since operations began in 2005 and an expanding team of collaborators, the CHARA Array has proven to be a reliable and scientifically productive facility for very high angular resolution studies pertaining to important problems in stellar astrophysics. An incomplete list of signature "firsts" includes:

- First direct detection of gravity darkening on a single star (α Leo).
- First direct measurement of the "P-factor" in the Baade-Wesselink method (δ Cep).
- Enabled first direct measurement of an exoplanet diameter (HD 189733b).
- Resolving unexpected emission inside dust destruction radius in YSOs MWC 275, AB Aur.
- First angular diameter for a halo population star (μ Cas A).
- First image of a single, main-sequence star (Altair).
- First direct image of an interacting binary (β Lyr).
- Shortest period binary yet resolved (σ^2 CrB – 1.14 days).
- First images of the eclipse event of the system ε Aur.

The addition of AO to CHARA will rest on the proven technical foundation of the CHARA facility. CHARA has demonstrated the faintest limiting magnitudes in the visible (R = 9) of any interferometer. In the infrared, the current CHARA K=8 faint star limit compares favorably with the 2008 advertised K=9 limiting magnitude for the Keck Interferometer (KI), and the current K=7.5 limiting magnitude of the VLT Interferometer[1] (VLTI), especially considering these systems have >70x more collecting area. The panel on Optical and Infrared Astronomy from the Ground in their report to the Decadal Survey stated that interferometry "should focus on advancing the technology while making interferometry more accessible to mainstream astronomers" and the ReSTAR report, written by a broad panel commissioned by the NOAO, recommended that "Access to O/IR interferometry should also be publicly available."

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[1] These are the correlated magnitudes, e.g. the magnitude for a point source. Note that Keck and VLTI are limited by vibrations and other factors in spite of years of remediation.

Indeed, CHARA has already volunteered public access time through the NOAO TAC process for the past 2 years. It is our belief, based on feedback from NOAO public time at CHARA and these reports, that the most important improvements for CHARA to move forward are sensitivity and scientific throughput. After extensive internal discussions, where we considered more telescopes, longer baselines, better UV coverage, different wavelengths, and new beam combiners, we concluded that AO was the most important technological development that can address these concerns. The CHARA Array is the only instrument in the world with baselines over 300m, simultaneous near infrared and high spectral resolution visible combination, and routine imaging capability - including a "snapshot" mode - and it represents the NSF's only major and on-going investment in ground-based long-baseline interferometry. AO is the logical next step of development for CHARA and would be the first major facility upgrade since construction began in 1998. This investment will ensure the competitiveness of US interferometry for the next decade against the better funded and larger groups in Europe operating in the South at the VLTI.

OVERVIEW OF THE CHARA ARRAY – The CHARA Array's six 1-m aperture Alt/Az telescopes are arranged in a Y-shaped configuration yielding 15 baselines from 33 to 331 meters and 10 closure phases (ten Brummelaar *et al.* 2005). These include the longest operational baselines in the world and permit resolutions, defined in terms of reaching the first null in visibility, of 1.6 and 0.4 mas (milliarcseconds) in the K and V bands respectively, or approximately 0.8 and 0.2 mas, respectively, for measurement of angular diameters. The layout of the CHARA Array is shown in Figure 1.

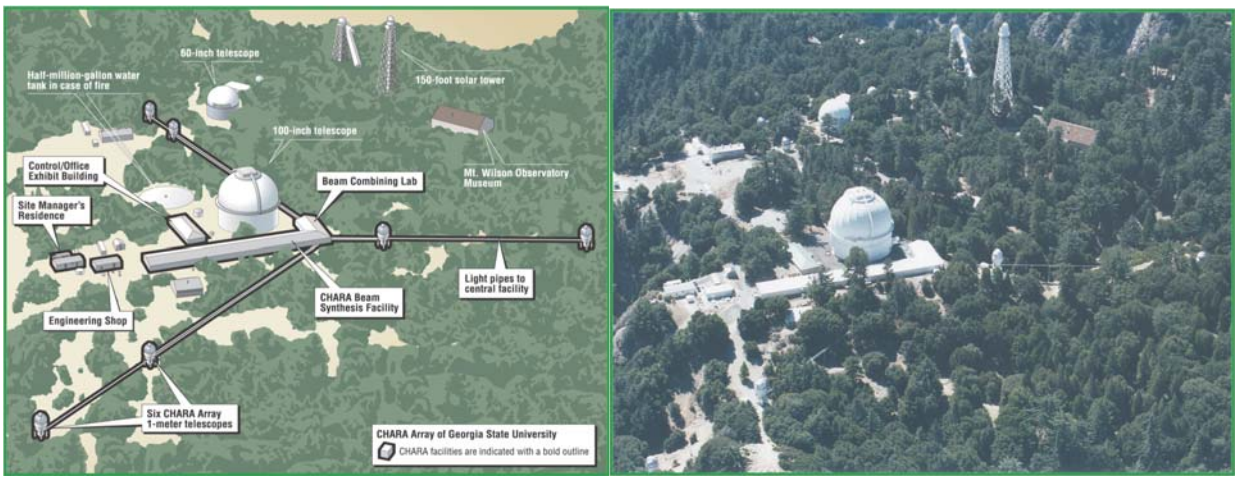


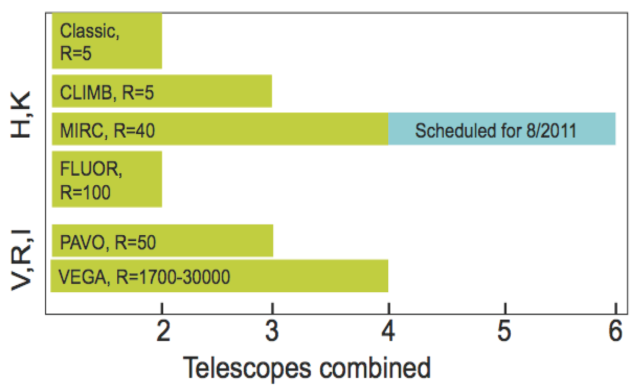
Fig 1. The layout of the CHARA Array on Mount Wilson California. Both the diagram and the aerial picture on the right are looking south from the north. The diagram on the left shows more clearly the major elements of the Interferometer including all six telescopes, the control building, the delay line building and the Beam Synthesis Facility in which we support 6 beam combiners from visible through to the near infrared.

Each of the six telescopes is an afocal beam reducer that injects a beam into the vacuum transport tubes. The primary and secondary substrates are of low-CTE materials and the secondary mirror is actuated for adaptive tip/tilt compensation. The custom designed mounts are exceptionally stiff and massive (23,000 lbs), and the structure is designed to maintain temperature-independent focus. Optical interferometry also entails the demanding requirement of zero optical path difference (OPD) through all arms of the array. This is accomplished at CHARA in two stages. The first occurs in vacuum and employs six parallel systems with remotely actuated mirrors moving to fixed delay segments. The second is a set of continuous 46 m long delay lines in air. A four-tiered nested servo system, with feedback from a laser metrology unit, tracks OPD to an rms error of 10 nm.

The interferometric beam combiner in which the scientific signals are recorded is analogous to the science camera in a conventional telescope. Through formal agreements between CHARA and several institutions, the beam combination capabilities of the Array have been very significantly expanded beyond plans envisaged in the original CHARA proposal, mostly with funds outside of NSF. These include the only capabilities found at any interferometer for closure phase signal recovery and high spectral resolution at visible wavelengths. The "CHARA collaboration" presently includes groups from l'Observatoire de Paris (Coudé du Foresto *et al.* 2003) the University of Michigan (Monnier *et al.* 2006, Berger *et al.* 2006a & 2008), the University of Sydney (Ireland *et al.* 2008), the NASA Exoplanet Science Institute at Caltech, and l'Observatoire de la Côte d'Azur (Mourard *et al.* 2010). Each of these groups has contributed to the development of the Array, primarily through the design and installation of new beam combiners (See Figure 2a).

SCIENCE HIGHLIGHTS FROM THE CHARA ARRAY – CHARA science has been continually supported by the NSF Astronomy Division for over twenty-five years and Array science has been supported since the fall of 2003 through competed NSF-AST AAG grants. While there is insufficient space in this proposal to present our scientific accomplishments in any detail, we hope that our ability to obtain and maintain GSU and NSF support for our continuing scientific efforts will be reassuring to reviewers.

Our core scientific focus is on measuring fundamental astrophysical parameters of stars – their sizes, surface temperatures, masses, and shapes – and exploring how these measurements affirm or challenge contemporary theories of stellar formation and evolution. The very long baselines of the CHARA Array give it access to almost all classes of stellar types and temperatures as evidenced by CHARA's contribution to stellar diameter measurements summarized in the Hertzsprung-Russell diagram of Figure 2b. Our new diameters have included stars on and off the main sequence with a concentration on domains inaccessible to other interferometers, and stellar types such as old, halo-populations stars (Boyajian *et al.* 2008) and the low mass M-dwarfs (Berger *et al.* 2006b).



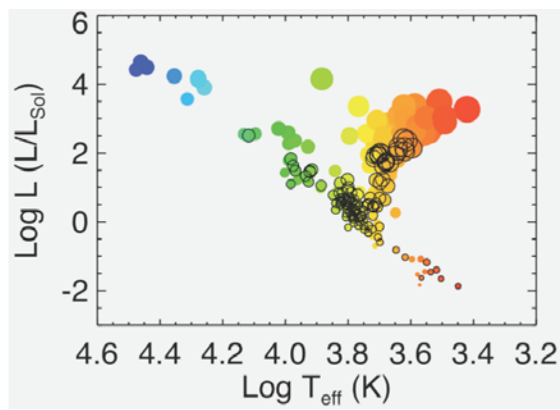


Fig 2a. (Left) Schematic description of beam combiners showing number of telescopes combined in each currently (green) and planned (blue). **2b. (Right)** CHARA measurements (outlined) are shown along with all other existing interferometric measurements of stellar diameters of 5% or better precision. The symbol sizes are logarithmically proportional to the stars' physical radii determined by combining interferometric angular diameters with distances determined by other techniques. (Figure by Tabetha Boyajian).

In addition to these diameter measurements, the Array is used to measure more complex structures related to stars and their environs. Rapidly rotating stars are subject to gross distortions of their surfaces into oblate spheroids. Figure 3a shows the image of the rapid rotator Altair (Monnier *et al.* 2007). This image, obtained with the MIRC beam combiner (Monnier *et al.* 2006), is the first ever made of a main-sequence star other than the sun. Similar studies have been carried out for the rapid rotators Regulus (McAlister *et al.* 2005), Vega (a pole-on rotator, Aufdenberg *et al.* 2006), Alderamin (van Belle *et al.* 2006), and Rasalhague (Zhao *et al.* 2009).

Other classes of stars receiving considerable attention are the Cepheid variable stars (Merand *et al.* 2005) that serve as one of the primary rungs in the cosmic distance ladder. In addition to measuring their diameters as a function of pulsational phase, CHARA/FLUOR (Coude du Forresto *et al.* 2003) measurements are detecting extended envelopes around these stars that likely produce small biases in Cepheid-based distance measurements (Merand *et al.* 2006 & 2007). Surveys of exoplanet host stars have been carried out to accurately measure the diameters of these objects (Baines *et al.* 2007, 2008a & 2009) as well as to rule out possible stellar rather than planetary companions (Baines *et al.* 2008b). Disks surrounding Be stars are detected through modeling (Gies *et al.* 2007) and imaging. Recently published results (Schaefer *et al.* 2010) show precession of the disk surrounding the star ς Tauri.

Binary stars have always been an important part of CHARA research (Csizmadia et al. 2009, Bruntt et al, 2010, Baines et al. 2010 & Raghavan et al. 2010). One such system, the 1.1 day period system σ^2 Coronae Borealis, is the shortest-period binary yet resolved (Raghavan et al. 2009). Another famous binary is β Lyrae, an interacting pair with one star filling its Roche lobe and supplying material to a thick disk surrounding its companion. The five images in Figure 3b, showing the pair at nearly quarter phase increments in the system's 9-day orbit, is the first imagery of an interacting binary (Zhao et al. 2008).

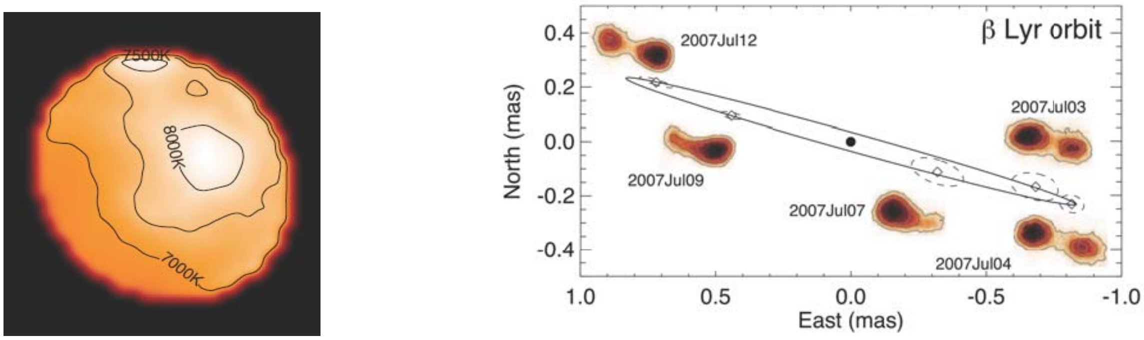


Fig 3a. (Left) This CHARA/MIRC image shows the oblateness and gravity darkening of Altair (scale 4x4 mas; Monnier et al. Science, 2007). **3b**. (Right) CHARA/MIRC imaged the β Lyrae system; the maximum separation between components is ~1 mas

More recently we have published images of the eclipse of the binary star ε Auriguae (Kloppenborg *et al*., 2010, Figure 4). The companion in this single-line spectroscopic binary has evaded direct detection for 175 years. For the first time interferometric imaging has revealed the eclipsing body, allowing us to measure the properties of the companion. Imaging the eclipse of ε Aur is a remarkable achievement for several reasons: it is a first - imaging an eclipsing body intruding on a stellar disk nearly 2,000 light years away; it confirms that a long-theorized disk is actually present; and it provides a rare tomographic view through a transitional disk that can be related to planet-formation studies.

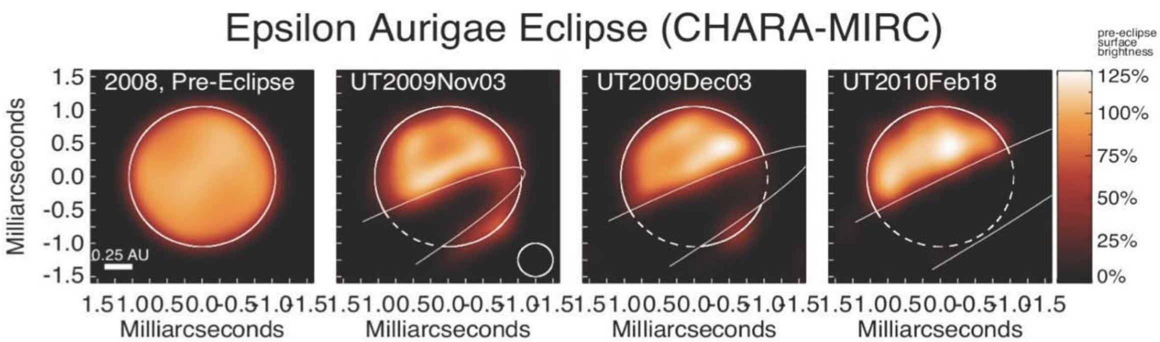


Fig 4. The first four images of the eclipsing binary star ε Aur (Kloppenborg et al. Nature, 2010) whose happens once every 27 years. We continue to image this object every month. Images of this kind require only a few hours of observational time.

This brief synopsis of the accomplishments of the Array during its first few years of science operations provides a basis for appreciating the scientific enhancements enabled by AO as described in the following section. These achievements also demonstrate that CHARA is a well-designed facility with broad scientific capabilities and that, though benefitting from a comparatively modest budget, it has been operated and managed to deliver world-leading scientific results. This context is critical since the proposed AO upgrade represents a major scientific investment in US astronomy infrastructure.

SEARCH ACTIVITIES TO BE ENABLED – The AO upgrade will enable a wealth of new high-impact science projects through the dramatic increase in R-band magnitude for tip/tilt tracking and the substantial improvement in near-infrared image quality. Table 1 summarizes the expected gains in cases of "poor" and "excellent" seeing (see technical description of proposed AO system for further simulation details). Figure 6b shows the current and expected R and K magnitudes in a graphical format.

The proposed upgrades at CHARA deliver powerful performance enhancements in three areas:

Technical Enhancement 1: Eliminating 19 reflections radically boosts visible tip/tilt tracking – The current tip/tilt sensing is done by a common camera for all telescopes located in the beam combiner laboratory (Sturmann *et al.*, 2006). A fundamental advantage of the proposed AO upgrade hinges upon moving the wavefront tip/tilt detection upstream from the lab into the individual telescope domes. By detecting the photons necessary for tip/tilt tracking at the telescope, we eliminate an extra 19 surfaces and associated aberrations and thereby increase the tip/tilt limiting magnitude by a seeing dependant factor of ~10-50. An additional boost is achieved by a state-of-the-art low-noise electron-multiplied CCD camera at each telescope. As is shown in the following sections, the increase in throughput also enables the inclusion of a low-order AO system while maintaining the dramatic improvement in tip/tilt tracking limiting magnitude. The improved R-band tracking is critical to increasing the number of observable young stellar objects (see Figure 6b) and other dusty objects.

Table 1. Sensitivity Improvements (magnitudes) using Adaptive Optics at CHARA
(value in parenthesis shows Phase I only "Static Correction + Tip/Tilt" upgrade)

	R band (tracking)	J band	H band	K band
"poor" seeing (r_0=7.0 cm)	+2.7 (+2.7)	+3.5 (+2.1)	+1.8 (+1.1)	+1.1 (+0.7)
"excellent" seeing (r_0=12.0 cm)	+4.7 (+4.7)	+2.9 (+1.9)	+1.5 (+1.0)	+0.9 (+0.6)

Technical Enhancement 2: Higher fringe coherence directly improves infrared limiting magnitude - In normal astronomical imaging, the limiting magnitude is simply related to the size of the telescope and quality of detector. For interferometry another equally important quantity is the "system visibility" which quantifies the degree of coherence between two interferometer beams. For perfect atmosphere and optics, this quantity is unity but is severely degraded by optical aberrations and wavefront errors, and is closely linked to the Strehl ratio of the optical system (ten Brummelaar *et al. 1995)*. Simulations, described below, show adaptive optics will provide system visibility gains in the near-infrared equivalent to 0.9 (K band) to 2.9 (J band) magnitudes. Indeed, the large J-band improvement will open up a new waveband which has not been utilized at all at CHARA to date. The marked improvements are based on correcting both atmospheric turbulence and reducing wavefront errors due to manufacturing tolerances and alignment errors in the existing beam train. AO wavefront stabilization will give more positive control over focus, alignment, and the pointing offsets required to compensate for atmospheric refraction. Table 1 shows that substantial improvement here will be achieved even with Phase I only because this stage includes a lab deformable mirror to correct for static aberrations in the optical train including the primary/secondary system. The full AO upgrade will have huge advantages at J band with diminishing returns beyond K band since r_0 becomes comparable to the 1m aperture of the CHARA telescopes.

Higher Strehl ratios are worth more than just better limiting magnitudes. For imaging studies of well-resolved objects in the photon-limit, signal-to-noise goes as the square of the visibility, which is effectively the square of the Strehl. Furthermore, better infrared performance can also be leveraged for greater visible light sensitivity since CHARA routinely uses its IR combiners as fringe trackers for the visible PAVO and VEGA combiners.

Technical Enhancement 3: Wavefront stability eliminates drop-outs in fringe tracking and single mode fibers – The AO system will stabilize the wavefront quality so that the system visibility is not just higher on average but is significantly more stable, especially at shorter wavelengths. The increased stability is important for continuous tracking of atmospheric turbulence for the infrared fringe tracking of faint sources, since even a short (few coherence time) drop in system visibility could mean total loss of fringe lock and increased overhead to re-acquire fringes. Indeed, fringe dropouts represent a basic limit of present systems (beyond photon or read noise - see detailed modeling of Lawson *et al.* 1999). More accurate visibility measurements and measurements of smaller visibilities both contribute to substantial gains in dynamic range, with improved detection of faint companions (e.g. Exoplanets) and low surface brightness image structure.

These three enhancements will enrich the reach of existing science projects with an order-of-magnitude more targets, improved precision, higher dynamic range, better image quality, and enabling in some cases higher spectral and/or spatial resolution. They will also improve the fraction of usable nights, resulting in more science productivity. The performance gains will also open previously unobtainable fields of astronomy. We discuss here specifically a breakthrough survey of T Tauri disks that will be possible with AO on CHARA and will highlight other significant new discovery areas.

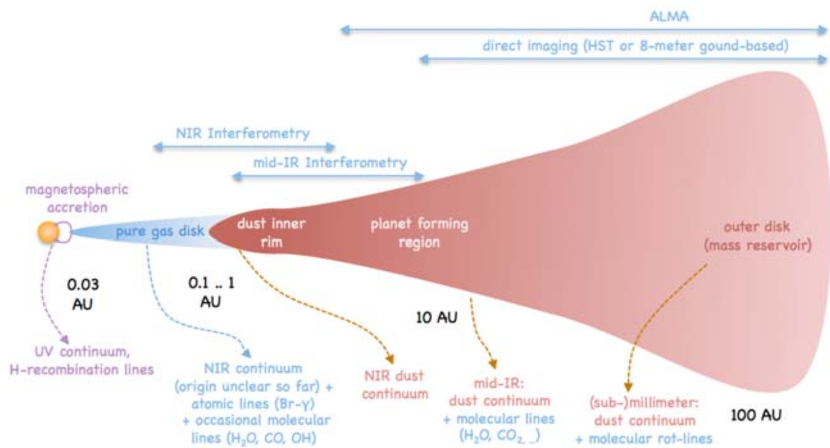


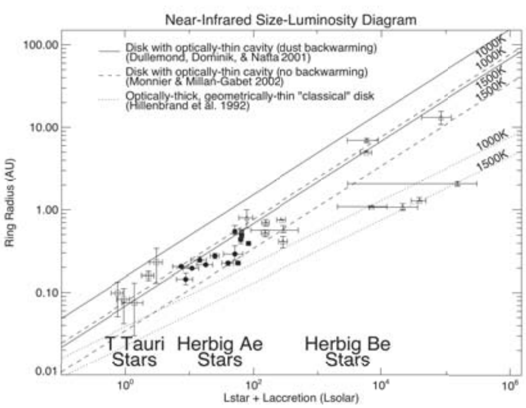
Fig 5. Schematic of a YSO disk (from Dullemond & Monnier, ARAA, 2010).

Key Project: Revealing the nature of T Tauri Disks - Infrared interferometers have made fundamental advances in our models of the inner AU of circumstellar disks around young stars. Millan-Gabet *et al.* (1999, 2001) first discovered that the dust evaporation radii at the inner edge of intermediate-mass Herbig Ae stars were many times larger than expected from the conventional disk models at the time. The first generation of interferometry results were summarized in Monnier & Millan-Gabet (2002), introducing the now well-established YSO size-luminosity relation. The large disk sizes were elegantly explained by the work of Natta *et al.* (2001) and Dullemond, Dominik & Natta (2001), using the mechanism of a "puffed-up inner wall" of dust directly heated by stellar radiation at the inside edge of the dust-rich disk. While these insights were first established for the higher mass and brighter Herbig Ae stars, they have had widespread implications for other young disks, especially the young solar analogues - the T Tauri stars. Figure 5 shows a schematic of a protoplanetary disk with the relevant regions labeled – here we are most sensitive to the near-IR emitting region within 1 AU of the central young star.

Akeson *et al.* (2005) and Eisner *et al.* (2007) showed that T Tauri stars have a size luminosity relation, although the sizes appear to be even larger than expected from the analogous Herbig Ae relationship (see Figure 6a). Various mechanisms have been suggested to explain these results, including scattering (Pinte *et al.* 2008), accretion heating, and reprocessing of the energy released as matter falls on the star (Millan-Gabet *et al.* 2007). Answers to this puzzle have been difficult to determine since T Tauri disks are much smaller in physical size than for the more luminous Herbig objects and also the disk emission is relatively less strong in the infrared. To make progress, we must increase our angular resolution and collect multi-wavelength data to constrain the size scale and emission mechanisms. Ideally, we would like real-time imaging to see how the disk structure varies with time and might respond to the fluctuating luminosity of the central source from variable accretion flows.

With the proposed AO upgrade, young star studies at CHARA will be revolutionized. To date, there have been only three published YSO results from CHARA. We are currently collecting data on 14 new targets - a time consuming process typically using the most sensitive single baseline beam combiner. In total, four T Tauri star have been observed so far with CHARA, due to the faintness both for the tip/tilt system and the infrared fringe tracking.

In order to illustrate how the combined R band and K band improvements affect the number of YSOs observable by CHARA, we have plotted all the Taurus YSOs (nearly all are T Tauri stars) from Kenyon & Hartmann (1995) in Figure 6b. There are approximately 11 YSOs (in Taurus) within the current reach of CHARA, while the number of targets increases to 61 when we consider the performance improvements using the proposed AO system for median seeing. Specifically, we gain 25 targets with a tip/tilt only upgrade that increases R-band sensitivity, an additional 22 sources by also including a static wavefront corrector to fix beam-train static aberrations, and lastly 3 more targets by using the full AO system. This simple estimate does not take into account that YSOs are generally resolved, which would make the full AO correction more critical. Also, as stated above, the AO advantage comes more dramatically at shorter wavelengths (J and H band) while this figure focuses just on K band. Our proposed upgrades will provide the crucial sensitivity boost required to keep CHARA leading in YSO interferometry for the coming decade.



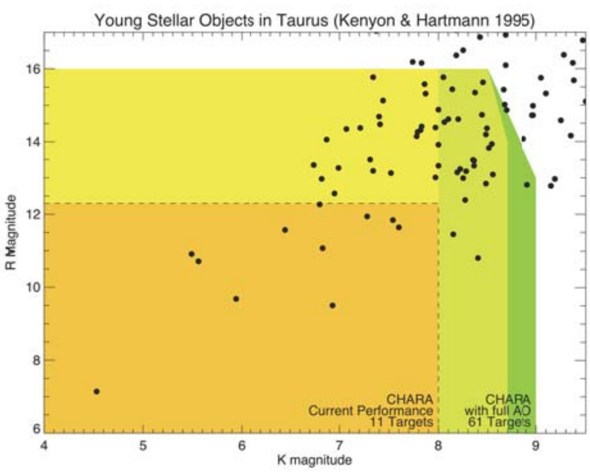


Fig 6a. (Left). The well-known (near-infrared) size-luminosity diagram for YSO disks (reprinted here from Dullemond & Monnier, ARAA, 2010). T Tauri disks are observed to be unexpectedly "over-sized" compared to their higher mass Herbig Ae counterparts. **6b.** (Right) The combined improvement in R band and K band limiting magnitudes will have a transformative effect on the study of Young Stars with CHARA (figure reflects improvement for median seeing). CHARA with AO can observe approximately five times more YSOs than the present system – virtually all the new sources are T Tauri stars. The other shaded regions show the incremental gains for tip/tilt only (pure yellow), tip/tilt with static wavefront correction (yellow-green), and full AO (green).

AO at CHARA will also allow interferometric imaging of a larger number of YSO sources. From our initial experience, fringes are often not found at intermediate baselines because the disk visibilities are too low (Tannirkulam *et al.* 2008ab). These low visibilities were a surprise and led to major changes in YSO disk models. The new generation of radiative transfer models suggests that interferometers need to track down to 10% visibilities to detect the faintest YSO fringes, and this will be made possible for the brighter targets with the expected improvement in telescope Strehl ratio and the concomitant increase in system visibility. In combination with the fringe-tracker CHAMP (Berger *et al.* 2006a) and the imaging combiners MIRC (Monnier *et al.* 2010) and CLIMB (Sturmann *et al.* 2010), detailed disk imaging of highly-resolved Herbig Ae/Be stars will be possible for about a dozen targets with K<7.0 (instead of K<5.9, currently). Note that for imaging T Tauri stars we will not need to detect very weak fringes since the unresolved star itself makes a greater contribution in the infrared,. Thus we expect to observe T Tauri stars to fainter magnitudes than for the Herbig case.

New Discovery Areas: Bringing breakthrough sensitivity to CHARA - Up to now, the only interferometers able to measure fringes on objects fainter than K>8 have required 8-m class telescopes (KI, VLTI). The priority to increase CHARA sensitivity is responsive to the demands of the community: many of the most competitive proposals from the recent CHARA public time (administered through NOAO) focused on the faintest targets. Our proposed upgrades will open up discovery areas for studying new classes of objects, including Active Galactic Nuclei (AGN) and Microquasars. Here, the full AO corrections are needed to take full advantage of the 1-m collecting area to make these faint objects feasible.

The brightest AGN (NGC 4151, NGC 1068, Whirlpool, etc) have a coherent flux of approximately K=9 (from the central engine only, not including the entire galaxy), and have been tracked at KI and VLTI (Swain *et al.* 2003, Kishimoto *et al.* 2009). Our AO models predict that a few of brightest AGN will be observable under the best seeing conditions at CHARA - this would truly be a breakthrough capability since CHARA possesses 3-5 times better resolution than these other facilities and AGN have only been partially resolved to date in the near-IR. Recent conceptual advances using clumpy dusty tori (Nenkova, Ivezic, & Elitzur 2002) in AGN have rested on the new generation of mid-infrared VLTI measurements and predict clear spatial signatures with CHARA angular resolution of <1 mas.

Microquasars represent an exotic class of objects that can be studied with an upgraded CHARA under excellent seeing conditions. The term *Microquasars* is given to a somewhat disparate population of systems in which a comparatively normal star is in orbit around a compact object such as a white dwarf, neutron star or black hole. Due to accretion onto the compact component, microquasars present astronomy with a window on truly unique phenomena. They are relatively near-field analogs of AGN and are laboratories for a wealth of unique physics including jets and accretion disks. SS433 is one of the brightest examples (R=12.2, K=8.2) and should be observable with the proposed upgrades**.** Because the underlying engine entails highly relativistic physics, studies have the potential for fundamental discovery with far-reaching impact. More specifically, interferometric measurements could contribute significantly to (1) characterizing the central dusty disk (2) understanding the connection between the accretion disk and the radio jet and (3) placing observational constraints on specific accretion/jet formation models. Other systems involving blackhole/NS star components will also be observable, including Cyg X-1, Vela X-1, LS5039, and LS I+61-303.

DESCRIPTION OF THE RESEARCH INSTRUMENTATION AND NEEDS – The AO requirements are based on known atmosphere and facility characteristics. The CHARA engineering stream includes tip/tilt data series for all operating telescopes, which are used to estimate r_0 in the Kolmogorov model. Also from the data archive, peak values of raw system visibility for the Classic beam combiner give the effective system visibility factor including atmosphere. Analytical models are used to estimate possible performance gains while a more sophisticated modeling approach is described below.

Small telescope AO for interferometry – Two decades of AO development for astronomy have produced a rich technology and body of experience. Multiple-high performance hardware products exist for the wavefront sensor (WFS) and deformable mirror (DM). The problem that we wish to solve requires only of order 30 sub-pupils. Such systems are not necessarily complex and expensive (Keller, Plymate & Ammons, 2003; Thor Labs, 2009), allowing us to use a more pragmatic approach than the intensive development needed for large telescopes. Nevertheless, an interferometric array does offer a number of special features. The CHARA telescopes produce a 125 mm afocal, tilt-corrected beam. CHARA also has large optical paths and many optical surfaces between the telescope and the beam combiner.

It is for this reason that we have engaged Dr. Chris Shelton of JPL/NASA as a sub-award of this proposal to act as systems engineer for the project. Dr. Shelton has been involved in the design and construction of numerous AO systems on a wide variety of telescopes and other applications, and is currently working on the 1476 actuator primary mirror control system for TMT. We have also assembled a team of external AO experts consisting of Dr. Dekany (Caltech), Dr. Ellerbroek (TMT), and Dr. Oppenheimer (AMNH), who will help oversee the design and development of the AO system .

The approach and selection of the concept – We have evaluated four configurations, differing in whether the DM and WFS are located at the telescope or in the beam combination laboratory. We only consider here options where the detector is on the telescope in order to achieve the best possible magnitude limit. Using analytical models we studied the performance of the AO and the impact on the performance of the interferometer. Our chosen configuration is conservative. The fast WFS and the DM will be located on the telescope in a relatively conventional arrangement. Unconventionally, we will have a slow WFS in the laboratory, in order to sense and remove non-common path (NCP) aberrations. Fast tip/tilt errors are not introduced in the primarily vacuum beam path from telescope to beam combination.

The *Big Beam* layout uses a 125+ mm DM in the collimated beam, and adds two optical surfaces to the interferometric path. The *New Secondary* layout has a new telescope M2 to provide a conveniently converging beam, and adds 6 new optical surfaces. The *Conventional* design uses a beam compressor and beam expander, and adds 7-9 optical surfaces. We find that hardware cost is similar. We have selected the *Big Beam* approach as our preferred option as it adds fewer surfaces and is physically very robust. We show the preferred reflected beam layout in Figure 7. A switchable mirror or beamsplitter at the m1 position can select the large FOV acquisition camera, pass the beam to the WFS, or select a reference stimulus source for back transmission toward the telescope. A flat beamsplitter at m2 transmits part of the stimulus light to a retroreflector in the center of the telescope secondary, to support end-to-end alignment, and reflects part of the stimulus reference wavefront to the WFS and to the laboratory for alignment and as an alternative to starlight for support of NCP measurements. The small number of additional surfaces in the interferometric path (only 2) ensures minimal *a priori* loss of throughput, and the configuration will allow the full array to remain operational over the weeks or months during which the AO optics are partially installed (possibly using existing flat optics in place of DM and dichroic). The DM does not exactly conjugate to the perturbed atmospheric layers, however numerical modeling shows that this is acceptable since the Fresnel length corresponding to a sub-aperture size of 16cm and a sensing wavelength of 650nm is 40km, and our pupil is conjugated only 0.3km from the primary mirror.

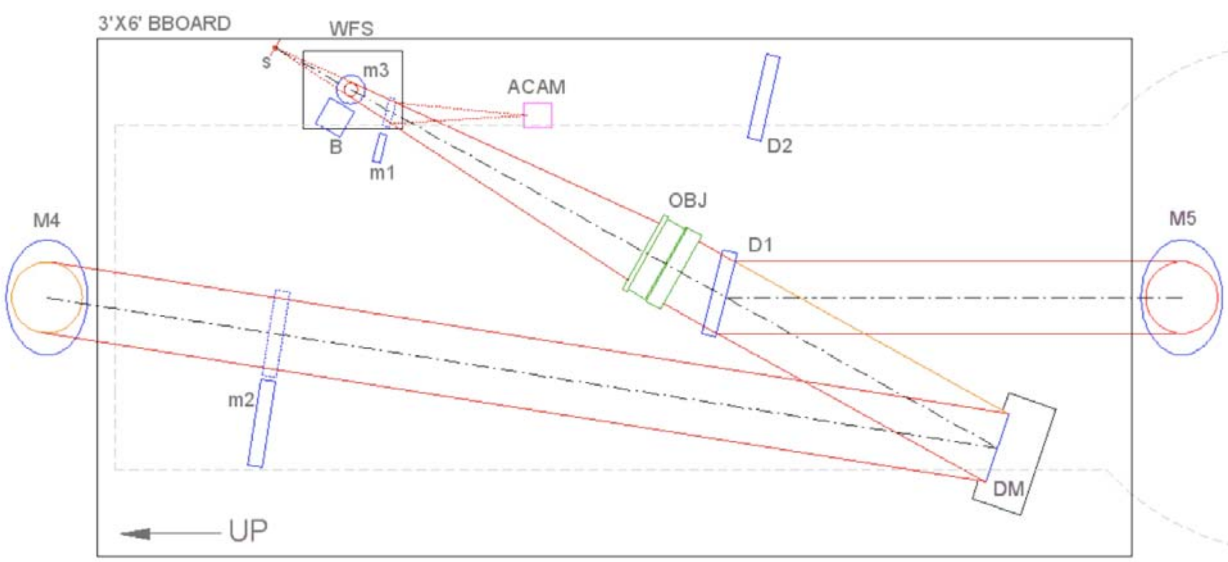


Fig 7. The *Big Beam* layout (rotated by 90°) with the components between the existing M4 and M5 telescope mirrors on the side of the telescope mount. In this position the instrument will be fixed with respect to gravity and is easily accessed. It will be enclosed except for remotely actuated entrance and exit apertures

The deformable mirror – CHARA AO requires a DM with actuators for ~30 sub-pupils. Several DM technologies are potentially useful for CHARA. We have a quote or ROM price from two vendors: Xinetics (PMN actuators on a rectangular grid), and CILAS (monomorph mirror with radial layout). Each vendor proposes a technology with which they have provided DMs that are in operation on the sky. Each offers actuator range larger than the required ~2 microns. Piston stability during DM operation will be maintained using techniques implemented for the existing tilt correction – piston-neutral DM motions and off-load to the fast optical delay control.

The dichroic and fast WFS – There are several dichroic strategies for infrared and visible/near-IR interferometry to enable separate or simultaneous operation of multiple combiners. We have verified dichroic substrate and coating availability from multiple vendors including Zygo and Barr, and have budgeted two sets. The fast wavefront sensor consists of lenses providing a correctly scaled and conjugated pupil image, a Shack-Hartmann lenslet array and a low noise camera. A large number of AO systems outside astronomy use an SH-radial bimorph combination, which is very stable against aliasing problems and easy to control in a modal configuration. We use WFS subapertures smaller than the DM actuator spacing to support such modal control. We also plan wavefront measurement of the SH spots by centroiding, as NCP errors will be compensated by implementing offsets in the centroid target positions. The centroid offsets will have a calibration error in variable seeing. These errors are mitigated by the small magnitude of the NCP errors and by real-time r_0 monitoring. An outer loop to drive the NCP pointing error to zero will be implemented using existing motorized flats. The optimal WFS pixel scale, and a decision whether to use square SH subapertures or a curvature-like radial geometry, will be determined by on-going simulations. Detail design, fabrication and test of the WFS will be done at the University of Michigan, a CHARA consortium member and, for this proposal, a sub-award.

The slow WFS – Our measurements show that the NCP error is not large, but with the operation of a nominal AO system, it will be the largest contributor of wavefront error for all but the faintest targets. The slow WFS in the laboratory will sense NCP errors. We are continuing to study the trades between simultaneous measurement of all beams with starlight and long integrations, and sequential measurement with a stimulus wavefront. The current tilt detection layout establishes the feasibility of placing all beam SH patterns on a single detector. Many suitable detectors are available.

Schedule and work breakdown – A preliminary design review (with outside expert participation) will be held 60 days after informal notification of award, so that the formal procurement process can begin on receipt of funds. The early implementation schedule is determined by finalization of system design, then by procurement time for major components, and after the first ~9 months, by the time required to carry out the design, fabrication and assembly of relatively routine opto-mechanical components.

<u>Milestones</u>

Notification of award:	+0 days – begin negotiations for major purchases
	+60 days – Preliminary design review
Formal receipt of funding:	+0 days – begin major procurements
	+ 90 days – WFS design review
	+270 days – Fast WFS and DM close loop in lab
	+360 days – First on-telescope installation
	+540 days – First interferometric tests, with remote operation
	+720 days – First system operational for science

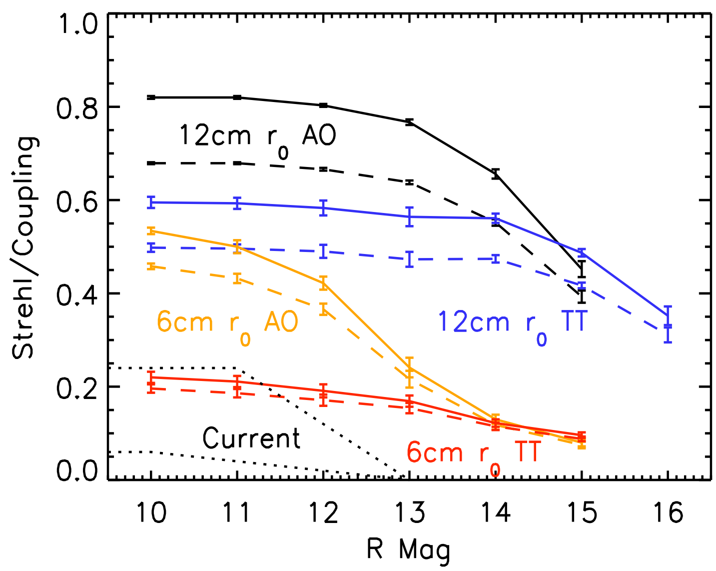
Third year – Install additional systems; implement slow WFS; refine control algorithms

Two-phase implementation – This proposal can be carried out in two phases if that better matches the ATI program resources. Phase I stands on its own technically and scientifically. Phase I provides the opto-mechanical changes and WFS implementation, the AO interface designs and prototyping. Phase I will also implement a slow DM for each telescope in the lab and this combined with the WFS capability will alleviate ongoing problems with static and slowly varying aberrations (Sturmann *et al.* 2010), thereby improving scientific performance beyond our current tip/tilt system. It delivers the full gains in tip/tilt correction, as shown in Figure 6b, with substantial payoff particularly in YSO and other faint-source science. It defers to Phase II the procurement of fast DM's and AO integration. The cost of Phase I is 56%

of the full two-phase project. If Phase I is funded by ATI, CHARA will use this fact as leverage to pursue other funding opportunities, including some private foundations that have assisted CHARA with supplemental funding in the past.

Performance characterization – We have used several tools to develop an understanding of the design trades for AO at CHARA. We have used classic analytical formalism in several independent realizations at several levels of sophistication (Ridgway *et al.*, 2010; Mozurkewich *et al.*, 2004, and an unpublished analysis tool offered by the UCSC AO summer school, modified by Nicholas Devaney and SR), and we have used a customized phase screen and Monte Carlo simulation approach (M. Ireland).

Fig 8 Expected Strehls (solid lines) and coupling to single-mode fibers (dashed lines) in H-band from our Monte-Carlo AO simulations for a 1-m telescope in H band. The 12cm r_0 case has a t_0 of 9 ms, and the 6cm r_0 case has a t_0 of 2.3 ms, representing roughly 80th and 20th percentile summer seeing. The "AO" curves correspond to the performance of the AO system as proposed. The "TT" curves correspond to improved tip/tilt and static correction only, as provided by Phase I of the proposal. The dotted lines show the current Strehl in the same percentile seeing conditions.



In the Monte Carlo simulation, we follow the light through the system and lock a realistic software adaptive optics system on the sensed photons. The simulation begins with a two-layer turbulence model with wind speeds that match the experimentally verified t_0 values for CHARA (e.g. 6 and 25 m/s for the "excellent" seeing case, 0 and 5000m above the telescope primary). Each layer has a Kolmogorov turbulence structure function. Wavefronts are sampled at discrete intervals of 1cm spatially and 2ms temporally, and are propagated through the atmosphere, AO system and interferometer using a Fresnel approximation. Science and sensor wavefronts are propagated separately. The deformable mirror and wavefront sensor are assumed to be in the same optical plane consistent with the design in Fig. 7: a demagnified image of the pupil as it would be 293m below the ground. For the purposes of the simulation, we use a square lenslet array with 16 cm on-sky subaperture spacing, and use the 31 actuator (19 within the pupil) deformable mirror from CILAS. The difference in geometry between the DM and WFS is therefore an integral part of the simulation, and we do not find that Strehl is significantly impacted by this difference.

In locking the AO loop, we assume a 4ms timing lag between sensing a wavefront and the DM moving, and for simplicity use a single reconstructor for all seeing conditions. We model the detector as an Andor DU860, including noise associated with electron multiplication, readout noise and 0.02 clock-induced charge events per pixel per frame. To stabilize the servo loop for faint stars, we clamp the denominator at 5 photons per frame per subaperture in the centroid calculation (Shelton 1997) and choose an exposure time that optimizes the Strehl. This avoids the need to change the servo gain when simulating faint stars. In addition to verifying the Strehls and magnitude limits listed in this proposal, we have also begun examining the performance of the slow wavefront sensor and visible light beam combiners with this code.

The analytical and Monte Carlo methods give predictions that are consistent considering the differing levels of detail and approximation. Figure 8 shows the Monte Carlo model results for the full AO project and for just Phase I, for parameters spanning the typical summer season conditions.

For many conditions, the AO performance is limited by the conservative 500 Hz loop rate. Significantly higher Strehl would be possible on all but the faintest objects with a higher speed. This may be possible with minor modifications to the Andor camera, if only a portion of the 128x128 sensor is used. Also, we follow CMOS detector developments for possible faster devices (Vu *et al.*, 2008). This and other design decisions remain on the table until PDR – however, the philosophy of the program is to adopt a cost effective solution rather than pursue every possible gain.

A known shortcoming of our analysis is the lack of Cn2 profiles specific to Mount Wilson. This is not likely to negatively compromise our results. The CHARA telescopes are mostly below tree-top level. It is expected and confirmed that a significant portion of the observed turbulence is at this level. This part of the wavefront error will be more correctable than the model atmosphere.

BROADER IMPACTS OF THE PROPOSED ACTIVITY – Human Resources Development: The CHARA Array is the only university-based interferometry facility of its kind in the world. Through its Department of Physics and Astronomy, GSU offers a PhD degree in astronomy with 24 graduate students presently enrolled full-time. During the past six years, the following students have completed their doctoral degrees based upon CHARA research: David Berger (2004 then held a postdoctoral position with U. Michigan, now in private industry), Chad Ogden (2005, now at Lockheed Palo Alto Research Center), Ellyn Baines (2007, now at NRL), Christopher Farrington (2008, remains with CHARA as Array Operator), Deepak Raghavan (2009, remains with CHARA as an adjunct scientist), and Tabetha Boyajian (2009, remains with CHARA as a NASA Hubble Fellow). Continuing CHARA graduate students and their completion dates include David O'Brien (Fall 2010), Rob Parks (Spring 2011), Yamina Touhami (Spring 2011) and Noel Richardson (Spring 2011). In addition, the Array has provided postdoctoral training for David Berger, Antoine Merand (now at ESO), and Gail Schaefer (currently supported by NSF).

Two CHARA students (Berger and Ogden) have been recipients of JPL Michelson Fellowships, Baines received an NRC Fellowship and has recently been named a Karle Distinguished Scholar Fellow at NRL, and Boyajian received a NASA Hubble Fellowship in 2009. CHARA is significantly contributing to the training of the next generation of experts in interferometry technology and science. Two graduate students at the University of Michigan received PhDs in 2008 and 2009 under the direction of Dr. John Monnier, and three post-docs have been involved in the CHARA/MIRC collaboration. The CHARA website (www.chara.gsu.edu) contains all CHARA Technical Reports, as well as many other technical documents, made easily accessible to the interferometry and broader community.

It is quite unusual for an urban university like Georgia State to operate a world-class astronomical facility, and this presents exciting opportunities not normally available to students attending a campus in a city environment. Furthermore, with remote operations now being routine no one is barred from working with, and within, the research group. The expansion of observing time and targets enabled by this proposal will inevitably lead to broadening opportunities for the participation of women, minorities and persons with disabilities in our research program.

Community Access: Since beginning science operations in 2005, CHARA has established formal collaborations with five groups (Paris Obs., Obs. de la Côte d'Azur, U. Michigan, Sydney U. and NOAO). This "CHARA Collaboration" has brought considerable expansion in the Array's complementary retinue of beam combiners resulting in more science opportunities. More than 70 researchers currently work within the CHARA Collaboration. The CHARA Array includes a full remote operations capability, with complete remote operations centers (ROC) on campus in Atlanta, Michigan, Paris, Nice and Sydney. These ROCs provide control over all observing functions of the Array, and allow faculty, staff and students at all levels to be trained in the use of the array, and to participate fully in research programs without the need to travel to the mountain.

All CHARA scientific data are maintained in a central archive at Mount Wilson, to which open access can be arranged as soon as support for public access becomes available.

CHARA has a tradition of documenting its technical developments with more than 150 internal reports and other documents available on its website at http://www.chara.gsu.edu/CHARA/.

Pursuant to our desire to open the Array to more general community access, CHARA partnered with NOAO in its 2009 call for proposals, offering fifty hours of service observing to proposals awarded time through the normal NOAO TAC process. Four of the 10 submitted proposals were assigned time during 2010, and three of those have been successfully completed at the time of this writing. Community access time was continued for the 2011 observing year, and 13 proposals for CHARA access were received by NOAO's submission deadline. That number is comparable to those for proposals competing for NOAO-allocated Palomar, MMT and Magellan time, and the time request for 2010 represented an over-subscription rate of 3.7. Our near-term goal is to significantly broaden community access by seeking support through programs such as ReSTAR and TSIP. Adaptive optics will increase the number of accessible objects and improve the amount and quality of the data, and therefore the science throughput. AO thus has the potential of greatly enhancing our program of open access in future years. CHARA is designing toward a future role as a significant community resource.

Enhancing Science Awareness Among Undergraduates: With an enrollment of 30,000 students and a location in downtown Atlanta, GSU is among the most diverse of large, research universities. Approximately 700 of these students are enrolled in introductory astronomy classes each semester, and all GSU astronomy instructors discuss the CHARA Array in their classes. We have had several undergraduate students, and even high school students, working with the group on campus and on the mountain, and we expect to continue interacting with undergraduate students. The CHARA Array is unique in the world, and with the improvements this proposal will fund we will be able to present research experience opportunities to students available at no other university.

Public Outreach – CHARA scientists frequently give tours of the facility to Mount Wilson visitors, as well as regular talks at local astronomy clubs in California and Georgia, along with television, museum, and web appearances. On four occasions, senior CHARA staff have been keynote speakers at national meetings of amateur astronomers. CHARA maintains an Exhibit Hall on Mount Wilson, the centerpiece of which is the historic Michelson 20-ft interferometer mounted atop the original prime focus cage of the 100-inch telescope. Back-lit displays and an interactive video kiosk were installed in 2009. During 2007, CHARA collaborated with the American Museum of Natural History in displaying the 20-ft in New York. As AO allows deeper and better imaging, we expect to add more displays to this exhibition highlighting the new abilities of the CHARA Array.

MANAGEMENT PLAN – The CHARA staff has extensive experience with electro-optical instrumentation. The proposed AO system is composed of a few modules: WFS, DM, several optical components, remote actuation, and a control system. Each subsystem is quite comparable to numerous Array subsystems that CHARA has successfully designed and implemented: fast tip/tilt detection and compensation, optical path difference detection and control, and atmospheric dispersion compensation. The AO control system shares many characteristics with existing Array control with respect to, for example, speed, nested servo loops, distributed multi-processing, and control GUI's. CHARA will carry out the AO design, development and implementation with the same small project, PI-led team approach that it has demonstrated with great success in the past. The CHARA staff will be augmented by the participation of Chris Shelton (JPL) who brings many years of AO experience to the project. Dr. Shelton will serve in the role of Systems Engineer, ensuring correctness and compatibility of design and interfaces, overseeing control system specifications, and leading on-telescope integration.

Soon after notice of an award is received, CHARA will formally convene a preliminary design review board to review the CHARA science goals, AO requirements, analysis, and design decisions. As previously stated, R. Dekany, B. Ellerbroek, and B.R. Oppenheimer have agreed to serve on this panel.

The wavefront sensor detailed design, fabrication, integration and testing will be carried out by our U. Michigan collaborators under John Monnier's direction. This team has experience with similar technologies, including low-noise detectors and precision alignment of lenslet arrays. Monnier's group is a long-term CHARA collaborator responsible for the MIRC and CHAMP beam combiners and also experienced with building instrumentation at UM, commissioning it at CHARA for common use, and interfacing to the Array control system. The fast WFS will be the main topic of a detailed design review ~90 days following kickoff, again including the panel of community experts.

The mounting of DMs, dichroics, and other optics will be planned and carried out by CHARA staff under the leadership of Dr. Laszlo Sturmann. CHARA has extensive experience with the issues of hands-off operation of precision equipment (the six telescopes are fully remote, as is most functionality in the beam train, optical delay and beam combination, including alignment), and the AO implementation will be entirely hands-off in normal operation.

The AO systems will be assembled on Mount Wilson, under the leadership of Dr. Judit Sturmann, who has extensive experience with assembling and operating CHARA interferometric opto-mechanics, and in defining and documenting alignment and operational procedures.

The slow WFS, will require conversion of the existing fast, laboratory 6-beam tip/tilt detector into a slow, low-order 6-beam wavefront sensor. This is a modest change to an operating sub-system, which however cannot be implemented until all on-telescope WFS are operational. The slow WFS will be the topic of the third planned design review. Required staffing is based on a component-level review, summarized above. Principal staff and levels of commitment are shown in the following table. Associated sub-award staffing is not included here.

CHARA personnel	**MM**	**Experience/Expertise**
T. ten Brummelaar (TB)	6	Interferometer systems, CHARA architect and programmer
L. Sturmann (LS)	6	Opto-mechanical design/test, hardware-software interfaces
J. Sturmann (JS)	6	Interferometric systems, alignment and calibration
Post Doc (PD)	15	Technically savvy scientist
N. Turner (NT)	6	Interferometric and AO systems, computers and networking
C, Hopper (CH)	24	10 yrs shop experience supporting CHARA
S. Ridgway (SR)	6	Instrument design, opto-mechanical devices
Consultants (C)	1.0	Expert review panel
Total	**70.5**	

The PI will hold regular work meetings/telecons with co-PIs and group leads. The PI will meet with the extended CHARA collaboration quarterly, or in the event of significant technical or budget events. As CHARA Associate Director, the PI has flexibility to balance staff effort on AO development with respect to operations and other activities. Note that CHARA normally closes scheduled observations for ~3 months each winter, allowing staff substantial uninterrupted periods of time for development work.

Risk mitigation is an important consideration of this program. Should a DM or detector selection prove unavailable, there are reasonable, affordable alternatives for each. Of the six CHARA telescopes, five will remain fully operational in non-AO mode until the first has been converted. Sequential conversion of the other five will then be a straight-forward, staged technical task. If for any reason a component does not perform to specification, the system performance will in most cases degrade gracefully, i.e. while peak performance may be compromised, functionality superior to non-AO operation will remain for all but catastrophic failures. The CHARA approach is very robust against delays, as there is no marching army – all key CHARA staff are funded from sources other than this proposal. If the schedule slips, this will not substantially increase project risk.

CHARA will be the first O/IR interferometer to implement small-telescope AO. We hope and expect that our experience will be beneficial to other arrays. The AO system design and on-sky

AO/interferometric performance will be fully documented at technical conferences and in the CHARA public web archive.

The current CHARA staff supports on-going operations and maintenance of the Array facility. Since lead responsibility and much of the hands-on effort for AO integration will be carried out by the permanent, on-site staff, the AO systems will be familiar and maintainable.

RESULTS FROM PRIOR NSF SUPPORT –

AST 0963172 - *Revitalizing Mount Wilson Observatory - $1,486,837 – 1 Oct 10- 30 Sep 12 – H.A McAlister PI* - Funds are to enhance the research related infrastructure of the Mount Wilson Observatory. This support is being utilized to repair and paint telescope domes and solar telescope towers, repair/upgrade potable and firewater delivery systems, repair/upgrade the Observatory machine shop, and to provide fire danger mitigation through brush and tree clearing. These upgrades will ensure the continued viability of Mount Wilson as an active research site.

AST 0908253 - *"Fundamental Stellar Parameters from the CHARA Array" - $894,115 - 1 Oct 09-30 Sep 12 - H.A McAlister, PI* - This grant was a renewal of AST 0606958. The results of science support for CHARA are described above.

AST 0606958 - *"Fundamental Stellar Parameters from the CHARA Array" - $706,158 - 1 Oct 06-30 Sep 09 - H.A McAlister, PI* - This grant was a renewal of AST 0307562. The results of science support for CHARA are described above.

AST 0307562 - *"Fundamental Stellar Parameters from the CHARA Array" - $755,867 - 1 Oct 03-30 Sep 06 - H.A. McAlister, PI* – The results of this first science support for CHARA are described above.

AST 0807577 – "*First Science with CHARA Fringe Tracker*" - $513,000 1 August 08 – 31 July 11 J. Monnier, PI. The postdoctoral research for this grant was hired in late 2009 and we have successfully helped commission the 3-telecope CLIMB combiner for initial YSO science, while demonstrating first 4-telescope fringe tracking with CHAMP fringe tracker and MIRC combiner simultaneously.

AST 0707927 - *"First Imaging Survey of Rapid Rotators and Be Stars with Long-Baseline Interferometry" - $287,537 - 1 Aug 07-30 Sep 10 – J. Monnier, PI. T.A. ten Brummelaar, Co.I.* –First results were presented at the 2009 winter AAS meeting, first paper published in 2010 on Zeta Tau (Schaefer et al. 2010), and new rapid rotator paper by X. Che will be submitted to ApJ in 2010 November.

AST 0335695 – *"Precision Imaging with Adaptive Optics Non-Redundant Masking Interferometry" - $189,069 – 10 Sep 03–15 Sep 06 – T.A. ten Brummelaar, Co.I.* – This project, with PI James Lloyd at Cornell, produced an aperture-masking camera placed behind the AEOS Maui AO system. The camera was successful, but the single observing run awarded as part of the grant was weathered out with no further time allocated. Lloyd has continued this project and published numerous papers based on Palomar data. ten Brummelaar ceased participation and has drawn no support after the first observing run.

AST 0352723 – *"Infrared Fringe Tracking with the CHARA Array Interferometer: Imaging YSO Disks and Faint Companions" - $830,221 - 1 Sep 04-31 Aug 07 – T.A. ten Brummelaar, CoI* - The CHAMP Fringe Tracker will vastly improve the magnitude limit of the MIRC and VEGA beam combiners. The CHAMP system, while behind the original schedule, is now fully constructed and has been installed on site. The first on-sky multiple baseline fringe tracking was achieved earlier this year We have documented our design in one SPIE conference paper (Berger et al. 2006a), as well as reporting the system performance more recently (Berger et al. 2008, Monnier *et al*. 2010). A YSO disk imaging program is underway with one paper recently published in ApJ (Tannirkulam et. al., 2008).