CfAO Theme 3
Extreme Adaptive Optics

Scot Olivier

CfAO Spring Retreat

March 21, 2003

ExAO Theme Overview Outline

- ExAO theme purpose and objective
- Scientific motivation
- Primary technical challenge
- Programmatic rationale
- Thematic emphases
- Theme accomplishments
  - CfAO MEMS roadmap
- Future Plans
  - eXtreme AO Planetary Imager
- Conclusions

Extreme Adaptive Optics Theme

- ExAO Theme Purpose
  - Development and utilization of AO systems and instrumentation to enable revolutionary ultra-high-contrast astronomical observations.

- ExAO Theme Primary Objective
  - Discovery and characterization of extrasolar planets through direct imaging
    - Unique capability for the study of planetary systems and their formation

Scientific motivation for ExAO Theme

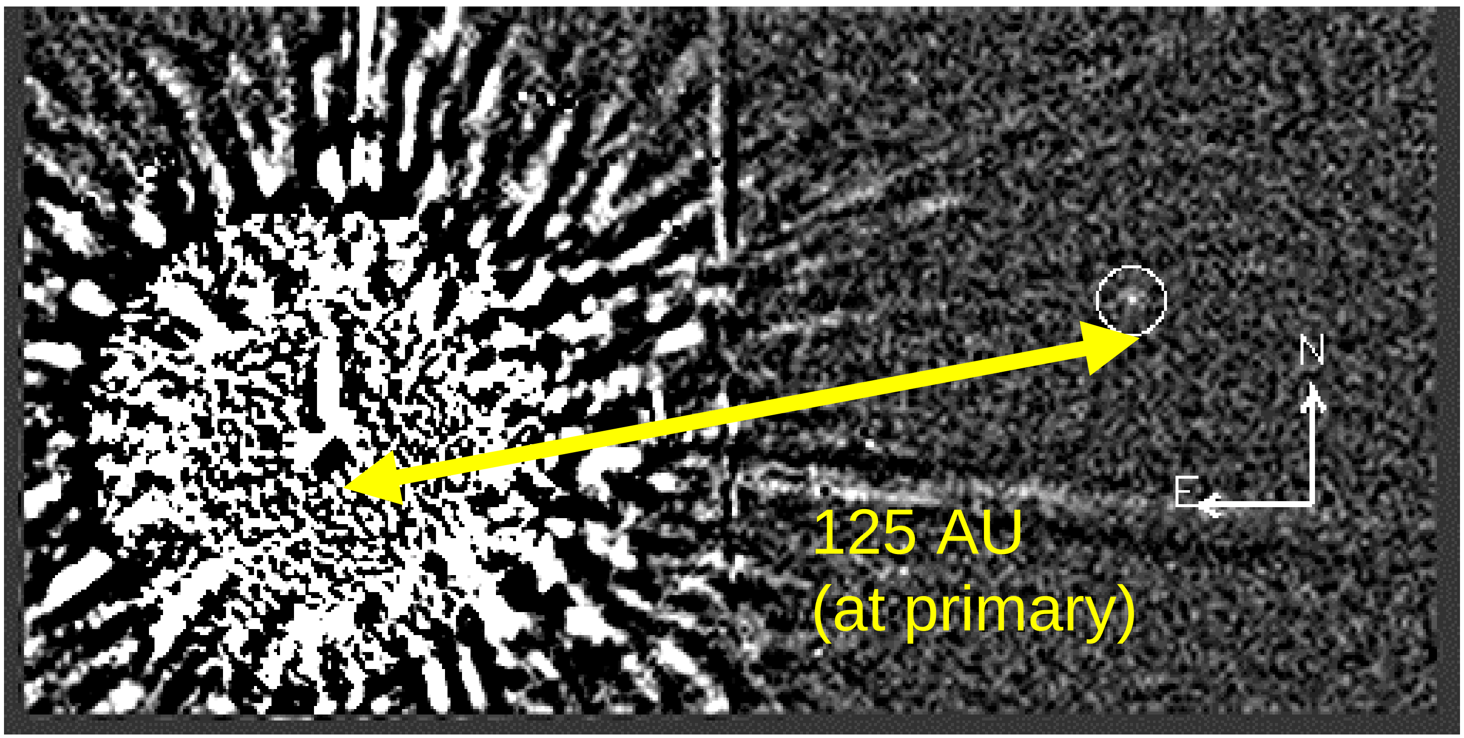
- More than 100 extra-solar planets discovered to date with radial-velocity spectroscopy
  - Sensitive to Jupiter-like planets orbiting at distances occupied in our Solar System by terrestrial planets.
  - Formation of these systems remains a puzzle, since Jovian planets had been hypothesized to form beyond the "*ice line*" at 4-5 astronomical units (AU; the mean earth-sun distance).
  - Unclear how to form the large ice cores thought to be required for the giant planets in our Solar System inside the ice line where heat from the star precludes the survival of frozen water.
  - Region beyond the ice line is largely inaccessible to indirect searches due to the need to measure an entire circuit of the planet's orbit for an unambiguous detection, requiring more than a decade of observation.

Scientific motivation for ExAO Theme

- *Direct* observation of planets enables detection of planetary systems like our own
  - Giant planets in wide (5-40 AU) orbits
  - Space for Earthlike planets in 1 AU orbits
- Direct observations allow characterization of composition and formation history of Jovian planets orbiting other stars
- Understanding formation and properties of giant planets is a crucial step towards understanding the frequency and properties of solar systems like our own

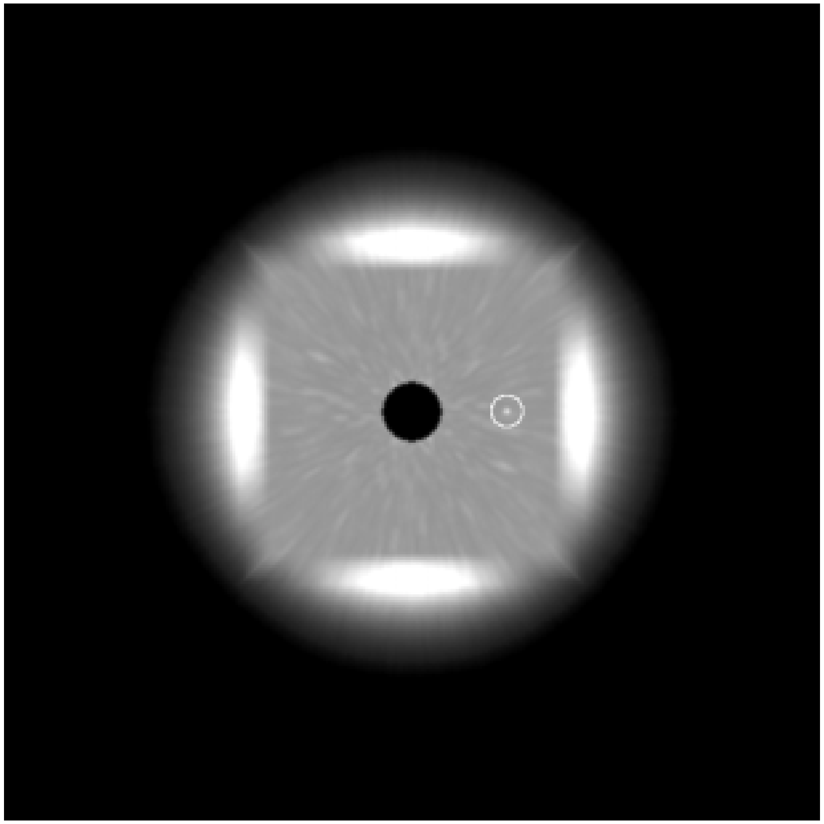
ExAO Theme Technical Challenge

- Detection of faint objects and structure is limited at smaller angular separations by the halo of scattered light



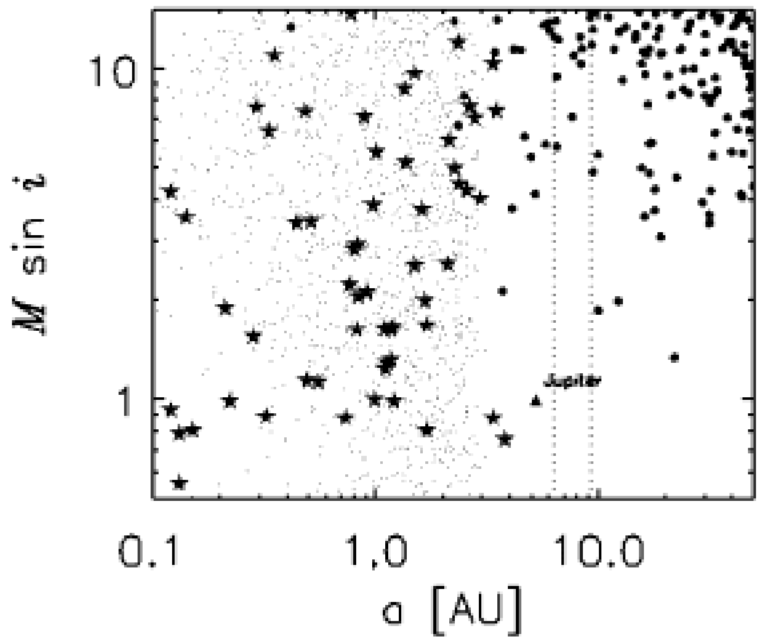
Example high-contrast observation using current Keck AO system

ExAO analysis confirms system on 8-10 meter telescope may directly observe Jovian planets



- Simulated image from the proposed eXtreme Adaptive Optics Planet Imager (XAOPI)
- 15 minute exposure at a wavelength of 1.65 microns
- Solar-type star (hidden behind an occulting spot in the center)
- 8 Jupiter-mass planet (circled, right of center)
- Square “null” in the scattered light created by XAOPI’s square deformable mirror and wavefront sensor

ExAO simulation demonstrates XAOPI detects significant sample of young Jovian planets



- Y axis is planet's mass (in units of Jupiter masses) times its orbital inclination (the quantity measured by radial-velocity surveys)
- X axis is planet's orbital radius in astronomical units.

- Monte Carlo simulation of a XAOPI search for planets orbiting nearby stars – compared to radial-velocity and astrometry techniques.
  - Stars represent known planets discovered by radial velocity surveys,
  - Dots represent a simulated astrometric survey using the Keck interferometer
  - Planets discovered by XAOPI are filled circles
- Only XAOPI has significant sensitivity to planets past the "ice line" where giant planet formation is expected to occur.

Programmatic rationale for ExAO Theme

- ExAO on **current** telescopes could enable new astronomical science within 3-5 years (within the CfAO lifetime)
  - significant improvement in sensitivity for the detection of dim objects near bright sources
    - e.g., planetary systems and precursor material
- ExAO could be a CfAO technology monument
  - world's most powerful AO system
    - better performance for high contrast science than any existing AO systems
- ExAO could be a step towards AO for extremely large telescopes
  - similar size, i.e., number of control points (~10^4)

Programmatic rationale for ExAO Theme

- ExAO takes advantage of the Center mode of operation
  - larger in scope and duration than typical single PI project
  - can be accomplished only by coordinating and combining research efforts of multiple researchers at several institutions
- ExAO emphasizes multi-disciplinary collaborations for the development of key enabling technologies
  - links to engineering research topics
  - industrial partnerships
- ExAO strengthens links between astronomy and vision science
  - MEMS deformable mirrors are being developed for both vision science and astronomical systems
  - current AO system performance characterization and optimization will address both astronomical and vision science systems

ExAO Theme Emphases

- *System design and analysis*
- *Instrumentation design and analysis*
- *High-contrast astronomical observations*
- *AO system performance assessment and optimization*
- *High-order MEMS development*
- *High-resolution wavefront control algorithms*

ExAO Theme Accomplishments

System design and analysis

- Improved performance models by extending the previous analytic work
- Performed detailed simulations to assess the capabilities of an ExAO system for direct detection of near-IR emission from extra-solar planets
- Demonstrated a survey of nearby stars would detect a large number of massive or young planets
  - Young planets have significantly enhanced near-IR emission.
- Showed that identifying and targeting younger stars would increase success rate by factors of 5-10.

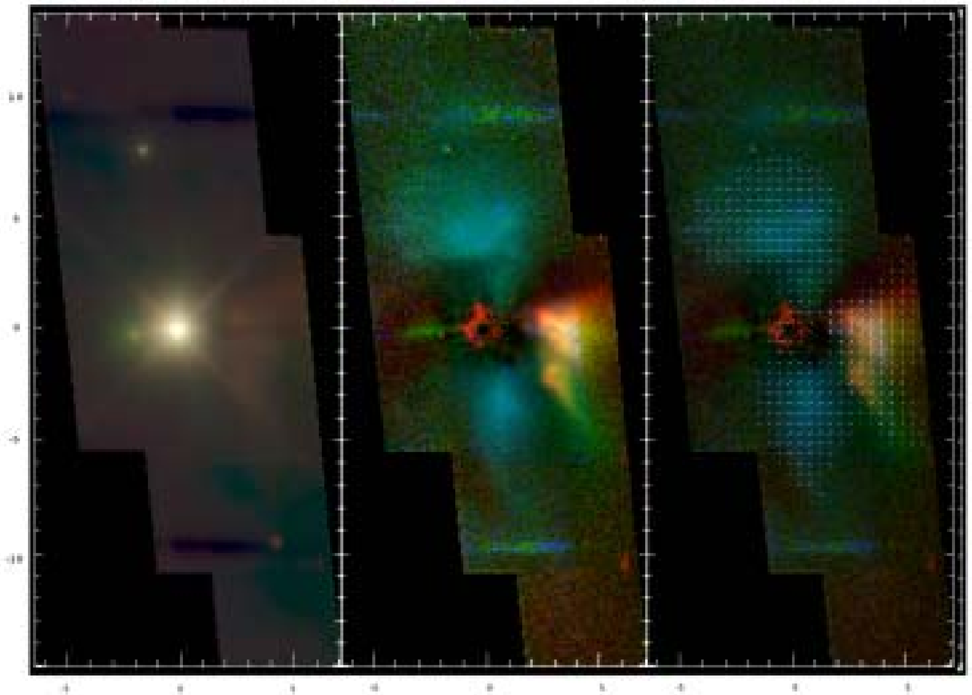
ExAO Theme Accomplishments

Instrumentation design and analysis

- Scientific utility of ExAO system enhanced by coupling with scientific instruments optimized for high-contrast imaging
- Developed imaging dual-channel polarimeter for use with the existing AO system at Lick Observatory.
- Instrument enhances sensitivity to star- and planet-forming dust near stars (which polarizes light) by removing the halo of light from imperfect AO correction (which is unpolarized), using a prism to image two polarization states simultaneously.
- Instrument developed for Lick saw first light in March 2002 and is unique because it is the first imaging polarimeter sensitive at near-IR wavelengths, ~2 microns, where AO systems perform best.

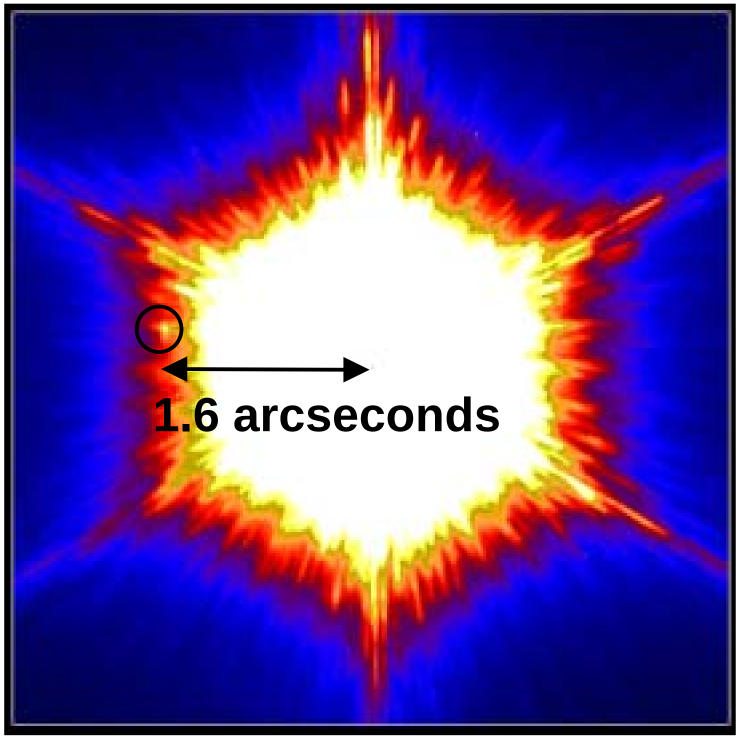
ExAO Theme Accomplishments

Instrumentation design and analysis



- Lick adaptive optics polarimetry observations of the Herbig AeBe star Lick Ha 234.
- ~5 Msun star still embedded in its natal cloud and probably less than 1 Myr old.
- False-color mosaic, blue = 1.25 microns, green=1.65 microns, and red=2.1 microns.

ExAO Theme Accomplishments



Candidate extrasolar planet orbiting a young star in Ophiucus.

High-contrast astronomical observations

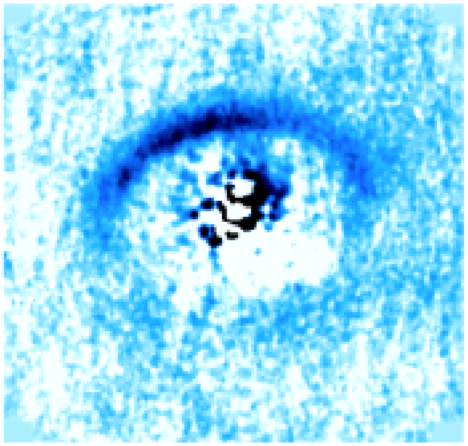
- Existing AO systems can be helpful in understanding the challenges of high-contrast imaging.
- We are pursuing forefront scientific observations of targets relevant to the ExAO science case.
- We have used these observations to aid in a systematic study of the high contrast performance of AO systems at Lick and Keck Observatories and to refine our AO performance models.

ExAO Theme Accomplishments

High-contrast astronomical observations

- Infrared images of GG Tau
- Strong forward scattering in Keck AO image shows evidence of dust grains beginning to coalesce

Hubble Space Telescope image at a wavelength of 1.6 microns.



Keck AO image at a wavelength of 3.8 microns

ExAO Theme Accomplishments

AO system performance assessment and optimization

- In order to anchor our models of ExAO system performance, it is imperative to understand the performance of current systems.
- Constructed accurate Keck AO simulation model, including effects of imperfections in the segmented Keck primary mirror.
- Compared measured and simulated stellar Keck AO image, demonstrating good agreement, particularly for the effects of known segment imperfections.
- Constructed detailed Keck AO error budget based on diagnostic data from the AO system in order to predict Strehl ratio.
- Ongoing research, carried out primarily by a CfAO-funded postdoctoral fellow resident jointly at LLNL and Keck, has led to identification of several key issues and moderate improvements.

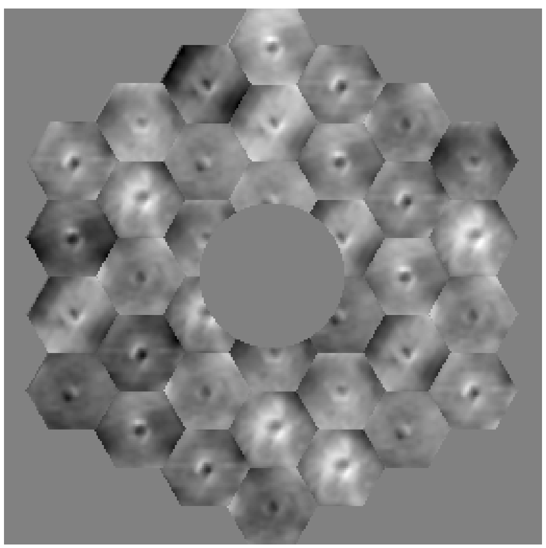
ExAO Theme Accomplishments

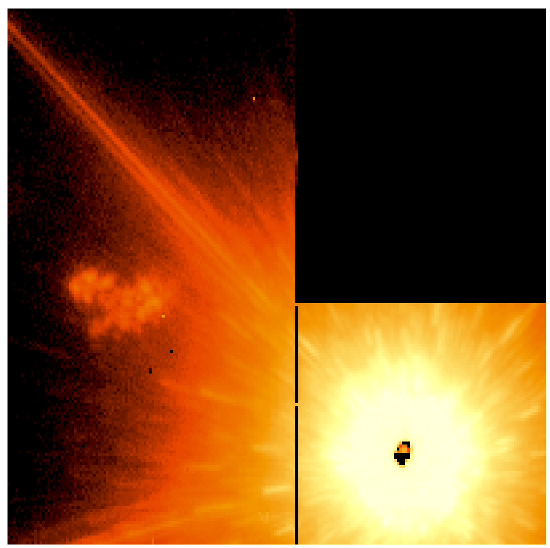
AO system performance assessment and optimization

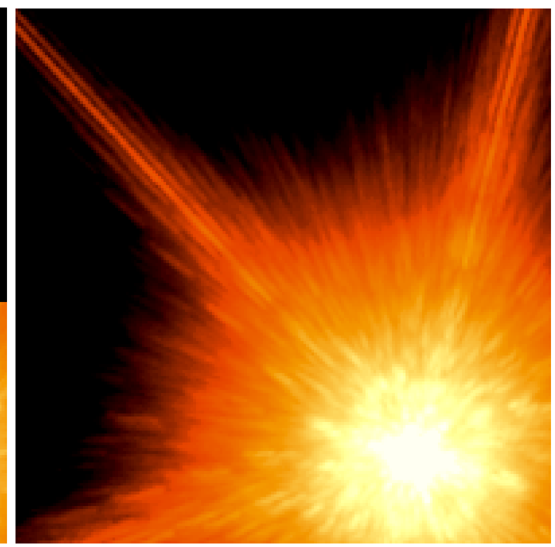
Simulated phase map of the Keck primary mirror showing errors due to segment positionsand central “dimples”

Deep Keck AO point spread function showing radial streaks scattered by dimple pattern

Simulated Keck PSF generated using phase map in 15a and Keck AO simulator code







ExAO Theme Accomplishments

<u>*High-order MEMS development*</u>

- Current straw-man ExAO system design calls for ~3000 actuators.
- MEMS technology offers the possibility of developing high-order deformable mirror for lower cost than conventional deformable mirrors.
- CfAO has pursued a highly collaborative coordinated strategy of MEMS development.
- MEMS deformable mirrors with architectures that allow scaling to over 10,000 actuators are being investigated.
  - Involves new packaging and electronics integration strategies.
- Also investigating actuator designs that allow scaling to over 10 μm surface motions and fabrication techniques that allow scaling of device sizes to over 10 cm.
- These efforts are coordinated with other MEMS projects in the CfAO for vision science applications, and with multi-institutional optical MEMS development efforts currently being directed by LLNL.
- Development activities in this area support not only the ExAO Theme, but also the ELT and Vision Science Themes within the Center.

CfAO MEMS roadmap
Vision Science (1 of 3)

Overall goals:

- **~200 actuators,**
- **~10 micron actuator range,**
- **>~100 Hz operating frequency,**
- **<~20 nm surface quality,**
- **>~97% fill factor,**
- **>~80 reflectivity in visible and near IR,**
- **clear aperture ~10 mm,**
- **unit cost ~$1000.**

Time scale:

- **ASAP – instrument development waiting for MEMS devices.**

Potential Alternative Technologies

- **Liquid Crystal Spatial Light Modulator**

CfAO MEMS roadmap
Vision Science (2 of 3)

Year 3

Boston Micromachines:

140-actuator MEMS DM ready for integration in prototype adaptive phoropter (30 nm surface quality, > 97% fill factor, aluminum coating, 2 micron actuator range, 7 kHz operating frequency, clear aperture 3 mm, unit cost $25k).

BSAC:

Demonstrated prototype actuator with 6 micron stroke, tip-tilt and piston operation, mirror segment surface quality of < 5 nm rms, and > 1 kHz operating frequency. Demonstrated mirror array bonding technique to enable > 97% fill factor.

Lucent (UC Berkeley):

Designing mirror to meet vision science goals with Lucent electret technology.

Year 4

Boston Micromachines:

Increase actuator stroke to ~4 microns, increase format to ~256 actuators.

Iris AO (spin-off from BSAC):

Develop integrated mirror with 6 micron actuator range, ~50 actuators with tip-tilt and piston, clear aperture ~3 mm, unit cost ~$25k. Extend actuator range to > 10 microns with > 100 Hz operating frequency.

CfAO MEMS roadmap Vision Science (3 of 3)

Year 4 (continued)

BSAC:

Transfer demonstrated actuator fabrication to SiGe process to enable integrated CMOS electronics (will improve unit cost).

Lucent (UC Berkely):

Develop mirror meeting vision science goals with Lucent electret technology.

Other MEMS DM efforts are being monitored for possible vision science application:

Intellite (Stanford spin-off), Stanford, Fraunhofer, Boston University (aluminum mirror) University of Colorado, JPL.

Year 5 and following

Continue to refine mirrors to meet vision science goals, particularly actuator range and integrated electronics for reduced unit cost and form factor.

CfAO MEMS roadmap
ExAO (1 of 2)

Overall goals:

- ~4000 actuators,
- ~5 micron actuator range
  - (can be ~1 micron if we cascade with low order AO system),
- >~3 kHz operating frequency,
- <~10 nm surface quality,
- >~99% fill factor,
- >~90 reflectivity in visible and near IR,
- clear aperture ~10 mm,
- unit cost <~$400k (ExAO proposal budget assumption).

Time scale:

- 2 years – consistent with current ExAO development plans contingent on co-funding and observatory selection.

Potential Alternative Technologies

- Xinetics photonics module

CfAO MEMS roadmap
ExAO (2 of 2)

Year 3

Boston Micromachines, Lucent (UC Berkeley), LLNL:

Demonstration of working system with 1000 actuators, ~1 micron actuator range, ~30 nm surface quality, > 5 kHz operating frequency, > 97% fill factor, aluminum or gold coating demonstrated, 9 mm clear aperture, unit cost ~$150k

Year 4

- **LLNL and Boston Micromachines will assess extension of 1000 actuator BMC DM to >~4000 actuators.**
- **Significant funding for this activity is expected from phase II of DARPA CCIT program.**
- **Increased actuator range to 5 microns, and techniques for improving surface quality, fill factor, and reflectivity (silver with overcoating) will also be evaluated.**

Other MEMS DM efforts are being monitored for possible ExAO application:

Intellite (Stanford spin-off), Stanford, Boston University, Lucent, BSAC, JPL.

Year 5

CfAO will issue an RFP for the ExAO DM, contingent on successful ExAO program PDR.

CfAO MEMS roadmap
ELT AO (1 of 2)

Overall goals:
- ~10,000 actuators,
- ~5 micron actuator range,
- >~3 kHz operating frequency,
- <~10 nm surface quality,
- >~99% fill factor,
- >~95 reflectivity in ultra-violet, visible, near and mid-IR,
- clear aperture ~30 cm,
- unit cost <~$1M.

Time scale:
- ~5-8 years – consistent with current ELT development plans contingent on funding.

Potential Alternative Technologies
- Xinetics photonics module, conventional DM with PZT or PMN actuators, deformable mirrors, including deformable secondary mirrors, with voice coil actuators.

CfAO MEMS roadmap
ELT AO (2 of 2)

Year 3

MEMS DM efforts are being monitored for possible ELT AO application:

Intellite (Stanford spin-off), Stanford, Boston University, Lucent, BSAC, JPL.

Intellite is working with LLNL to demonstrate a process with a ~10 cm clear aperture.

Year 4

CfAO will help assess technologies (in cooperation ELT construction projects) and consider proposals to address key ELT AO challenges for MEMS DM's, particularly clear aperture requirements.

The DARPA CCIT program is expected to fund development of MEMS DM's with clear apertures up to ~10 cm.

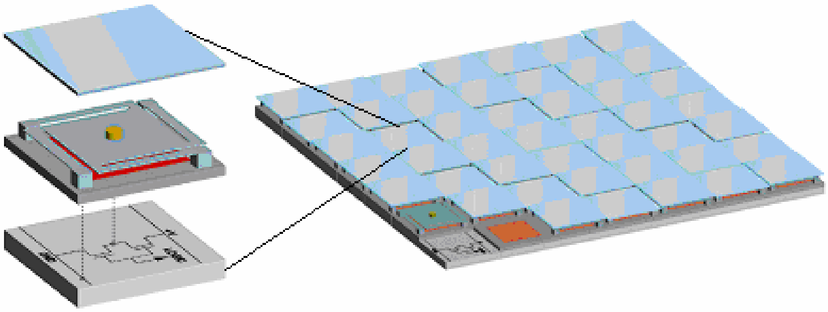
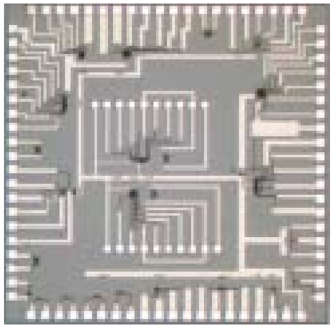
Year 5 and following

Based on evaluation of technologies, CfAO may help coordinate MEMS development for ELT AO (in cooperation with ELT construction projects).

ExAO Theme Accomplishments

High-order MEMS development

- Prototype 1000-actuator MEMS deformable mirror developed at Boston University (left).
- Illustration of scalable electronics integration strategy with high-voltage CMOS amplifiers located under each actuator (center).
- Prototype high-voltage CMOS amplifier developed at LLNL for use with Boston University MEMS DM (right)..

ExAO Theme Accomplishments

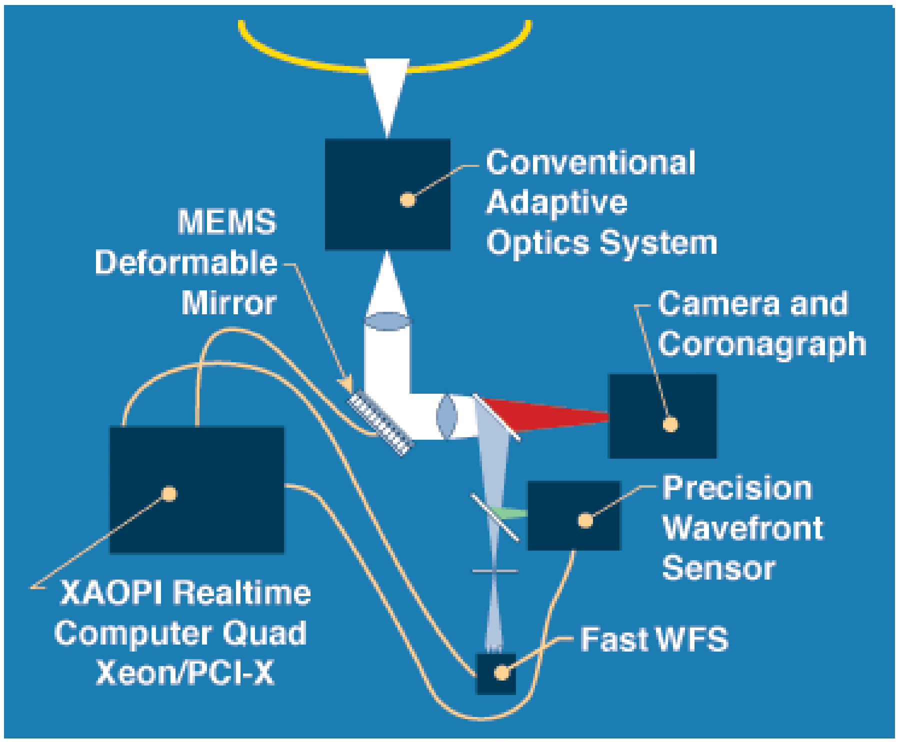
High-resolution wavefront control algorithms

- ExAO systems require simultaneous control of more degrees of freedom than have previously been demonstrated in an AO system for astronomical imaging
- Activities to demonstrate the feasibility of the required high-order, high-speed wavefront control.
  - Demonstrated high-order control using a liquid crystal spatial light modulator with ~300,000 phase control points.
  - Work on efficient reconstruction algorithms has concentrated on Fast Fourier Transform (FFT) techniques.
    - Simulated direct comparisons to conventional reconstruction schemes for large systems, and demonstrated nearly identical performance with a dramatic decrease in computational requirements
      - Factor of ~80 improvement for a 3000-actuator system.
    - Experimentally validated new FFT reconstructors using the AO system on the Palomar Hale telescope in September 2002
- Future work will compare FFT reconstructors with other efficient algorithms

ExAO Theme Future Plans

- In years 5-10 the CfAO will carry out a tightly integrated program with three components.
  - Continue high-contrast science with the Keck and Lick AO systems.
  - Develop a highly accurate interferometric wavefront sensor operating directly on starlight.
  - Design and implement the eXtreme AO Planetary Imager (XAOPI – pronounced “zow-pee”),
    - Incorporating the world’s most advanced AO system, with ~3000-actuators, on an 8-10m telescope.
    - Total proposed cost of ~$6 million (not including the science camera)
    - Expect CfAO to fund less than half the overall cost of the XAOPI project
    - Combination of NASA, private foundations and other NSF programs to fund remainder
    - Science camera also funded from other sources

XAOPI Schematic Layout



Straw man design

- 64x64 MEMS deformable mirror,
- Conventional Shack-Hartmann wavefront sensing, and
- Fast reconstructor algorithms
- Commercial computer hardware
- Low-bandwidth, high-accuracy wavefront sensor providing direct wavefront measurements at all times
- Budgeted overall residual rms wavefront of ~70 nm
- Closed-loop bandwidth goal of ~120 Hz,
  - Wavefront sensor frame rates of ~2000 Hz
  - Control loop time delays of ~0.5 ms

XAOPI Project Plan Milestones

Date	CfAO Year	Milestone
Summer 2003	4	Conceptual design review and telescope selection
2003	4	Apply for external funding
Winter 2004	5	Preliminary design review
Spring 2005	6	Critical design review
2005	6	Subcomponent construction (LLNL, UCSC, CIT, JPL)
2006	7	System integration and testing (UCSC)
2007	8	First light, telescope integration and testing

XAOPI Risk Reduction

- Major risk areas
  - Suitable MEMS or other deformable mirror
  - Architecture that integrates into a specific telescope
  - Need for external funding.

- Risk reduction strategies
  - Extensive design review process with external reviewers at all stages of the project.
  - Each review stage will provide a formal report to the CfAO, observatory, and external funding agencies.
  - CfAO will continue its yearly evaluation of this project via the annual proposal review cycle.
  - Consider alternatives to our primary MEMS vendor, including semi-conventional deformable mirrors from Xinetics.
  - Design concepts that include integration into specific telescopes will be pursued during the current year, leading up to the conceptual design review.

Conclusions

- Highly integrated program represents strong example of CfAO researchers operating in "Center Mode".
- Program team offers a balanced combination of science qualifications and technical abilities
  - Includes experience accrued from the design and astronomical use of the Palomar, Lick, and Keck AO systems for high dynamic range science.
- ExAO Theme operates with regular telecons, meetings between individual participants, and workshops on ExAO system design.

- We have explored the properties of ExAO beyond initial idealized cases, produced sophisticated predictions of high-contrast AO performance, and developed a compelling science case connected to a technologically feasible AO system.

ExAO Spring Retreat 2003 Sessions

- Advanced Deformable Mirrors – MEMS AO Technology
  - Friday, 10:00-12:15
- ExAO Science Progress
  - Friday, 4:15-5:30
- ExAO Technical Workshop I
  - Saturday, 9:30-10:30
- ExAO Programmatic Workshop
  - Saturday, 10:45-12:15 (CHANGE)
- ExAO Technical Workshop II
  - Saturday, 1:30-3:00 (CHANGE)
- XAOPI calibration and interferometry
  - Saturday, 3:15-4:45
- AO Performance Workshop Planning
  - Saturday, 4:45-5:30