5.0 Collaborative Proposal

5.1 List (all institutions) of Proposal Participants:

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Time Scale: Multi-year

5.3 Collaborative Abstract

Technical Abstract
We propose to continue a major scientific legacy project from CfAO -- the CfAO Treasury Survey (CATS). We are using adaptive optics at three 8-10m telescopes to observe a large, deep sample of galaxies in the early universe with the goals of 1) observing the assembly of galaxies from smaller subunits to larger ones like our own Milky Way, 2) measuring the rates of star formation and the evolution in stellar populations, 3) discovering the highest redshift supernovae, and 4) characterizing central active galactic nuclei (AGNs) throughout the past 10-12 Billion years. CATS will disseminate an archive of forefront AO data and associated reduction and analysis tools, as a community resource to explore some of the grandest and most profound problems in cosmology.

CATS is planned to last through all of the 2nd five years of CfAO, and to focus on the largest Hubble Space Telescope (HST) fields designed for faint galaxy surveys. These presently include two GOODS (Great Observatories Origins Deep Survey) fields (N and S), the GEMS field (extension of GOODS-S), COSMOS (an equatorial field near 0230-04), and one of the four DEEP fields known as the Extended Groth Strip (northern field near 1415+52). These regions of the sky are being intensively studied by the world's most powerful ground and space telescopes, spanning a energies from radio to X-rays. All are expected to produce their deepest images to date. CATs will provide near-infrared images, a critical missing wavelength range, at a resolution (0.05 arcsec) comparable to the optical diffraction limit of HST. The near-IR is particularly valuable because it penetrates dust obscured regions, is sensitive to old stars, and, for high redshift objects measures light that was emitted as visible photons, allowing direct comparisons to extensive optical studies of local galaxies. The CATS program is envisioned to take dozens of Keck, Gemini, and Subaru nights, with significant repeat observations to reach fainter limits, gain larger fields of view, and detect variable AGN and supernovae. Measurements of kinematics and spectra at high spatial resolution in the near-IR will begin late in CfAO Year 6 with the OSIRIS integral field spectrograph (led by co-PI Larkin) on the Keck Telescope.

From fall 03 through spring 05, the CATS team was awarded 10.5 nights of Keck natural guide star AO time and 4.5 nights at Keck for spectroscopic follow-up. In fall 04 and spring 05 the team was awarded a night of laser guide star (LGS) AO time on Keck, from which a paper in ApJ Letters has been accepted for publication. Most importantly, the team was awarded 4.5 nights of Keck laser guide star AO time for fall 05, representing 45% of the total UC allocation of LGS AO time(!) We initiated a plan with Fred Chaffee, Director of Keck Observatory, to obtain non-AO optical redshift data in the GOODS-North field in spring 2003; these data were released to the astronomical community in 2004. STScI has agreed to collaborate in developing a CATS public archive and database. A science paper based on laser guide star AO data collected in Oct 04 is in press (Ap J Letters).

CATS provides a superb Center-mode activity by unifying previously separate science programs, by providing an excellent technology platform for pushing and demonstrating the power of AO, by disseminating AO data and associated reduction and analysis tools, and by focusing on the most intensely studied fields in the sky. Based on work to date, CATS is an excellent vehicle for growing broad community interest in AO.

Non-Technical Abstract

We are pursuing a five-year CfAO Treasury Survey (called CATS). CATS is using adaptive optics to observe a large, deep sample of galaxies in the early Universe. The goal of this legacy scientific program is to track the assembly of galaxies like our own Milky Way, and to characterize its history of star formation. The near-infrared adaptive optics (AO) observations will be 4 times sharper than those obtained by the Hubble Space Telescope. The scientific value of the adaptive optics data will be highly leveraged, and will achieve high visibility in the broader astronomical community because the chosen sky fields all have complementary observations at other wavelengths, using space-based images at optical and x-ray wavelengths, and ground-based images at radio wavelengths. We will make our AO data available to the public in an on-line archive. We expect to observe supermassive black holes that are enshrouded by dust in the very early universe, and supernova explosions that can be used to measure the curvature and "dark energy" of the Universe.

5. 4 Collaborative Proposal

5.4.1 Technical Description

Despite enormous advances in observational data from ground and space, in theoretical understanding of the physics of the early universe and structure formation, and in powerful computer simulations over the last decade, four of the most fundamental questions in cosmology remain unanswered:

1) What is the nature of dark matter?
2) What is the nature of dark energy?
3) How did galaxies form and evolve?
4) How did massive black holes in the centers of galaxies (AGNs) form and evolve?

Due to the broad impact and inter-relationships among dark matter, dark energy, galaxy formation, and AGN formation and evolution, astronomers who can study the past directly by observing very distant objects gain an advantage that is unique. But this advantage is gained with three major problems:

Distant objects are generally very faint
Distant objects are generally very small
Distant objects have light shifted from the optical regime (a part of wavelength space rich in information about the physical conditions and chemical abundances of gas and about the star formation history), to near-infrared wavelengths.

The keys to progress have been the advent of bigger telescopes on the ground to reach fainter limits in imaging and spectroscopy; the use of Hubble Space Telescope (HST) to resolve smaller scale features in galaxies; and the use of the near-infrared to probe the red-shifted optical light. With the development of adaptive optics on very large telescopes such as Keck, astronomers have, for the first time, the tools to gain in all three arenas simultaneously. Until the 20-30m class telescopes are completed with multi-conjugate adaptive optics (MCAO), Keck and other 8-10m telescopes have the opportunity to provide unique data. Although HST has the advantage of having a darker sky

background because above the atmosphere, HST's 2.4m mirror provides 4x blurrier images than a diffraction-limited 10-m telescope. Even the James Webb Space Telescope (JWST) will have only a 6=m mirror and thus will not have superior spatial resolution to Keck with adaptive optics in the near-infrared.

We are leading a major AO survey within the CfAO that will obtain these data in the most intensely studied regions of the sky. The present targets are regions selected from major HST survey fields using the Advanced Camera for Surveys (ACS), and designed for study of the distant universe: the GOODS (Great Observatories Origins Deep Survey) fields north and south, the GEMS (Galaxy Evolution from Morphology and SEDs) field, the COSMOS (Cosmic Evolution Survey) field, and the EGS (Extended Groth Strip) field. Each of the GOODS fields covers a small region (10x16 arc min); GEMS covers a somewhat larger region of 30x30 arc min centered on GOODS-South; COSMOS covers a region of 60x60 arc min in a spring equatorial field, and EGS, a field of 10x60 arc min in the northern spring sky. All four fields are being studied by an international consortium of over 100 scientists using the Hubble Space Telescope in the optical, the Chandra X-Ray Space Telescope and XMM in the X-ray regime, the Spitzer Infrared Telescope Facility (Spitzer) in the mid and far infrared, and several of the world's largest ground based telescopes. These fields are being studied so intently in order to gain a broad-wavelength view of a large sample of galaxies in the early Universe. The non-X-ray space telescopes will achieve close to diffraction limited performance and all are expected to produce of their deepest images ever. What is missing from all these surveys are near-IR images at spatial resolutions comparable to the 0.05 arc sec achieved by HST in the optical. By using AO on the Keck, GEMINI, and Subaru Telescopes, CATS will provide the scientific community with unique and valuable data in the near-infrared gap.

Only by combining the resources of many telescopes and wavelengths will astronomers be able to probe the diversity of physical processes that are involved in understanding distant galaxies. Only with the 0.05 arc sec resolution of an AO system on an 8-10m class telescope will many of the key subcomponents of galaxies (bars, spiral arms, bulges) be resolved in the near-IR, or the brightness of nuclear emission or supernova atop its host galaxy be measurable to useful accuracies. Only with significant and repeated observations will astronomers be able to secure the necessary variability data to detect and measure the photometry of supernovae (used for the determination of the dark energy fraction), and dusty AGNs to study the evolution of massive black holes.

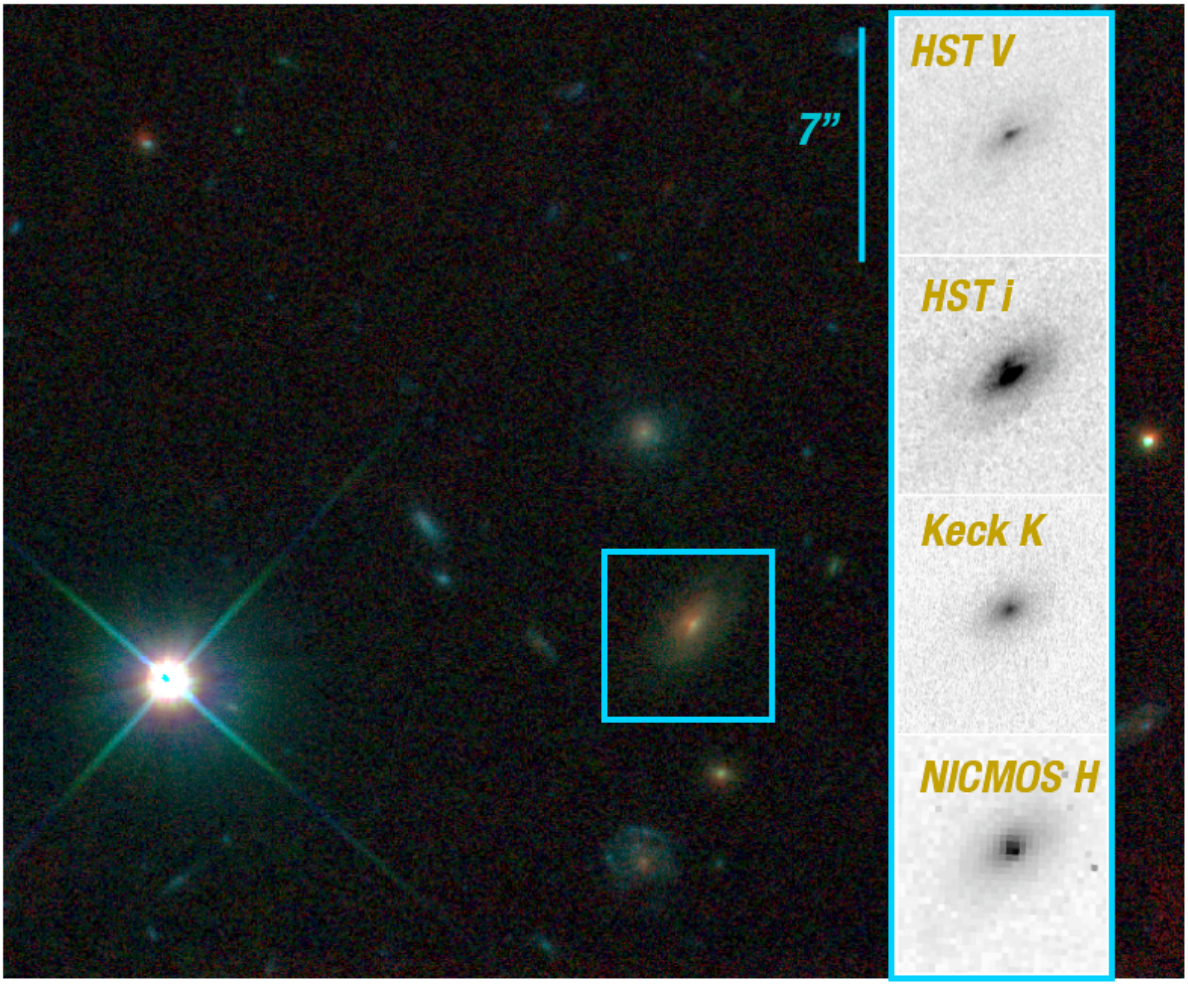


Fig. 1 An example of CATS data: This NIRC2 image is an hour exposure taken in Mar 2005 with the Keck laesr guide star AO system. The field is located in the Extended Groth Strip where HST ACS and NICMOS-3 images exist. The right hand panel is a blow-up of one galaxy and shows the superior spatial resolution in the near-IR achievable with the Keck AO system (resolution of 0.05 arcsec) compared to the HST NICMOS-3 image (spatial resolution of ~0.20 arcsec). Such AO resolutions allow unique studies of small subcomponents within distant galaxies, such as bulges (see example below the marked galaxy), bars, AGNs, and supernovae.

CATS is a major observing program that began with 5-10 nights of natural guide star observations per year, and is ramping up to 10 - 15 nights per year from Keck and comparable amounts from GEMINI and SUBARU. With over 5000 square arc min of sky part of the GOODS, GEMS, EGS, and COSMOS fields, more than 1000 square arc min are accessible to the laser guide star AO system now operational on Keck. Since AO camera fields are still narrow (typically less than 0.5 square arc min), several 100’s of nights would be needed to cover the entire AO-accessible area assuming exposures of 1 hour per pointing. Even more time would be needed for deeper exposures, more filters, and for extensions to spectroscopy. Thus CATS is in the luxurious position of being able to choose the very best subfields in terms of guide star brightness, surface density of galaxies, numbers of AGNs, etc. Besides providing the best AO data possible, CATS is also providing

coordination among different AO surveys of distant galaxies, and will support timely dissemination of AO data and requisite software to the broad astronomical community.

Planned Year 7 Activities:

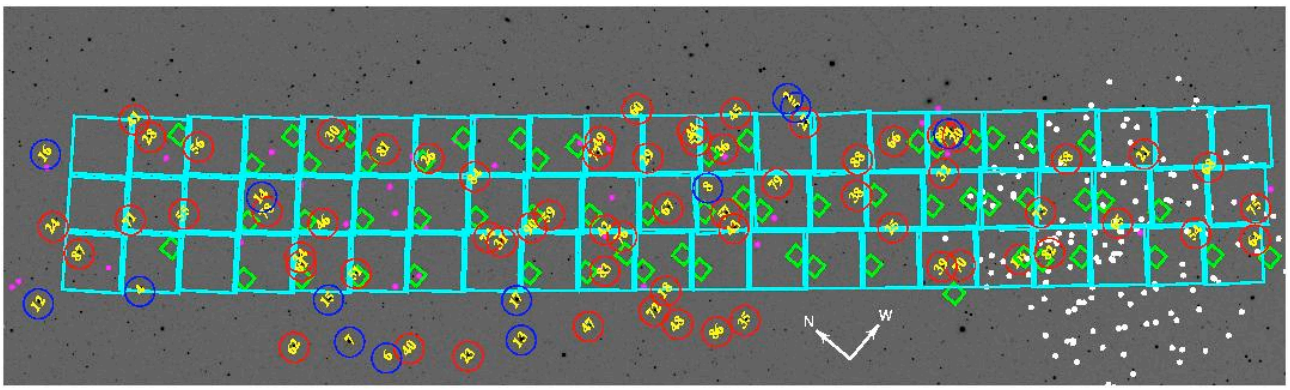
Year 7 of the CfAO will see many important accomplishments for the CATs program. It is expected that both the Laser Guide Star (LGS) system and the OSIRIS spectrograph will be under normal operation on the Keck Telescope. We will begin serious work on the data archive structure. Here are some of the highlights planned for Year 7:

1) We aim to complete 5-10 more nights on the Keck Telescope observing both NGS and LGS targets in the GOODS, GEMS, COSMOS, and EGS fields. Taking into account lost time due to bad weather, this should result in about 100 hours on targeted fields. A rough breakdown of time would be:
   a) 50 fields at 1 hour depth => 600 galaxies down to H~23rd magnitude
   b) 5 fields at 6 hours depth => 150 galaxies down to H~24th magnitude
   c) 10 targets with the OSIRIS/IFU at 2 hours depth
2) We will use the optical, x-ray and mid-IR data that will be publicly available to characterize the galaxies in the CATS fields.
3) We will test PSF characterization schemes both for NGS and LGS targets. This is a crucial step before releasing data to the community.
4) We will use the OSIRIS integral field spectrograph to observe roughly 10 galaxies. This will allow for the first ever measurements of internal dynamics on sub-kpc scales in "normal galaxies" in the early universe.
5) We will make a serious start on the CATS archive in Year 7, in conjunction with STScI and the other GOODS and EGS teams.

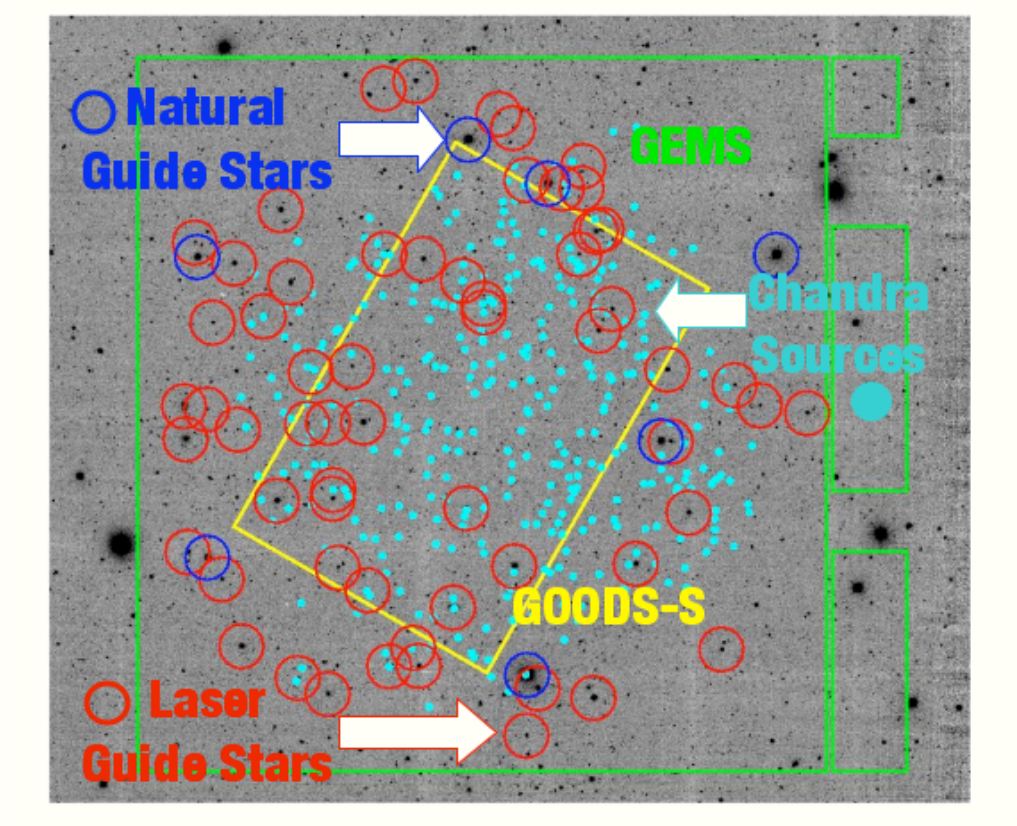
Planned Years 8-10 Activities:

During the final 3 years of the CATS program, we envision using 1/4 of the observing time to perform deep integrations (8 hours per field), 1/4 time on integral field spectroscopy, and 1/2 of the time on the slightly shallower imaging survey (1 hour per field). This will yield data on a large number of galaxies, while providing a statistically meaningful sample of fainter objects and kinematically "dissected" galaxies. Year 8 of the CfAO should see the second release of data to the community with well characterized PSFs.

A conservative estimate of the number of galaxies to be observed in all 3 parts of the program is 1000 galaxies, with roughly 20% at z>1, and approximately 25-50 galaxies with integral field unit spectroscopy with OSIRIS. All will have optical, x-ray, and mid-infrared observations, although we anticipate some will be undetected in one or more wavebands. We also anticipate more than 10 high redshift supernovae, about 50 high redshift AGNs, and an unknown number of serendipitous targets such as halo white dwarfs.



Above: Figure 1. New CATS Field, the Extended Groth Strip



Figures 1 and 2. Potential observing coverage of the new EGS field (top) and the GOODS South region (bottom), both already observed with multi-band HST ACS imaging. The EGS is 10x60 arc min; the GOODS-S is 10x15 arc min. Not shown are the GEMS field (30x30 arc min) and the COSMOS field (85x85 arc min). Both the EGS and GOODS-S fields have relatively few available natural guide stars (stars with V < 13 mag, circled in blue). Shown in red is the vastly larger coverage possible with LGS AO centered on much fainter tip-tilt stars (V < 18 mag). The white dots in the EGS and the blue dots in GOODS-S show the density of relatively rare Chandra X-ray sources. Non-X-ray galaxies (difficult to depict on this scale) are at 100 x greater densities. The EGS image above also shows the locations of HST NICMOS-3 images (green diamonds).

5.4.2 Relation to a CfAO Theme

The study of galaxy evolution is a well-identified goal of multi-conjugate AO (MCAO) on extremely large telescopes (ELTs). The CATS legacy program is providing several important stepping stones to that goal, and will produce dramatic science results that demonstrate the power of AO for faint imaging and spectroscopy and draw the attention of the international astronomy community.

A common idea among astronomers is that AO works well on point sources or at least point-like objects but is not well suited for quantitative measurements of extended or low surface brightness sources. Our current work is beginning to demonstrate the usefulness of AO for faint galaxy science. With the high profile nature of the GOODS, GEMS, EGS, and COSMOS fields and the high leverage from the deepest data at other wavelengths and timely dissemination of high quality AO data to the public, CATS will draw attention throughout the traditional astronomy community and help to inform astronomers about the true power of AO on large telescopes.

Besides paving the road to the science case for ELTs with MCAO, CATS is serving as a technology platform by requiring the most challenging AO performance and efficiency. CATS is pushing the development of optimal observing strategies at the telescope (the CATS team is already making significant improvements in the observing efficiency of the Keck LGS AO system), the development of new software for handling spatially and time variable PSFs, especially with laser guide star systems, and for extraction of scientifically useful astrometric and photometric data from AO data. CATS is driving the need for improved simulations, for guiding performance tradeoffs in the development of AO instruments, and for gauging random and systematic errors from AO and MCAO measurements. Finally, by releasing AO data both in raw and processed form, the broader community will have the opportunity to participate in improving AO technology and software for useful science as well as gaining understanding of the advantages and limitations of using ELTs with MCAO.

5.4.3 Nature of collaborations

The CATS team is very well coordinated and has excellent communication between UCLA and UCSC. We (students, postdocs, and faculty) observe jointly at Keck, share data analysis tools, and write papers together. We have regular videocons, with many informal communications taking place between videocons. This close communication is a real success story for the "Center" aspects of the CfAO.

Larkin at UCLA and Koo at UCSC, as Deputy PI's of CATS have been coordinating the CATS program since CfAO Year 4 and will be helping Max (as PI) lead CATS during the remaining second term of CfAO. The following serves as tentative division of tasks, though divisions are somewhat artificial, since both Larkin and Koo will be involved in all aspects of CATS.

Larkin will have responsibility for coordinating the following areas from within the CfAO and broader astronomical community.

1) Acquisition of early Lick Laser AO data and Keck NIRC2 AO data.

2) Other observatories with AO.
3) Link to instruments and technology (Larkin is PI of the AO spectrograph OSIRIS which is currently undergoing commissioning).
4) Instrument simulations for performance characterization and tradeoffs.
5) Distant galaxy and serendipity science (shared with Koo).
6) PSF characterization of AO data and algorithms for its determination (shared with Koo)

Koo will have major responsibilities for coordinating the following areas within CfAO and the broader astronomical community:

1) HST and other major facilities operating at wavelengths outside of the near-IR.
2) Data simulations for measurement accuracy and errors for structure; stellar population; astrometric; and kinematic analysis from AO data.
3) Website, archive, and data release for CATS.
4) Education and public outreach products from CATS.
5) Distant galaxy and serendipity science (shared with Larkin).
6) AGN science (shared with Max)
7) PSF characterization of AO data and algorithms for its determination (shared with Larkin)

Meetings*:* Regular meetings to discuss progress and problems take place. Besides the frequent and regular videocons we have been holding, we anticipate holding several short face-to-face workshops among the participants and other CfAO members interested in CATS throughout Year 7. We will also hold the second CATS workshop for a broader community, so as to obtain feedback and gain visibility for CATS during its formative stage.

5.4.4 Roles of each participant and site

Claire Max - PI (UCSC): Overall lead, interpretation of data for AGNs
James Larkin - Deputy PI & co-PI (UCLA): see 5.4.3
David Koo - Deputy PI & co-PI (UCLA): see 5.4.3
Matthew Barczys - grad student (UCLA): working with Larkin full-time
Mark Chun – staff (U. Hawaii): link to Subaru and Gemini AO programs
Sandra Faber - faculty (UCSC): PSF characterization
James Graham - faculty (UCB): Serendipity science
Raja Guhathakurta - faculty (UCSC): AO photometry
Jennifer Lotz – postdoc (Arizona): merger structure, spectroscopy of CATS targets
Jason Melbourne - grad student (UCSC): CATS as part of PhD thesis
Anne Metevier – postdoc (UCSC): kinematics and galaxy substructures
Scott Severson – staff astronomer (UCSC): AO photometry & spectroscopy
Andy Sheinis – faculty (Wisconsin) – AGNs and galaxy kinematics
Michael McElwain (UCLA)- graduate student
Eric Steinbring – staff (HIA-Canada): external collaborator with access to CFHT
Marianne Takamiya – staff (U of Hawaii): near-IR expertise, galaxy substructure
Shelley Wright – grad student (UCLA); working with Larkin at full-time

5.4.5 Collaborations outside CfAO and cross disciplinary links between Astronomy and Vision Science. See proposal from co-PI Larkin.

5.5 Specific Year 7 and Multi-year Schedule and Milestones:

CATS in Year 7 will be in production mode – increasing its database of AO observations of distant galaxies and completing science papers that use AO in the near-IR. Assuming full funding, the data archive will finally make substantial progress.

Date & Milestone:

1) Jan 2006 Complete a total of 10 NIRC2 LGS AO pointings of 1 hour exposures of GOODS, GEMS, EGS, & COSMOS fields; yield will be first 100 distant galaxies to H ~ 23 with multiband HST optical images.

2) Mar 2006 Complete proposals for Keck LGS AO time with NIRC2 and OSIRIS for fall 2006. Submit one science paper based on Keck NGS AO data from 2005 and earlier CATS data.

3) Jun 2006 Submit one science paper based on Keck LGS AO from 2005; science will include the nature of distant bulges and disks, near-IR structure of distant AGN galaxies, and/or nature of z ~ 2 galaxies.

4) Jul 2006 First public data release, collaboratively with HST STScI, of Keck LGS AO data and PSF's for scientific community; present CATS LGS results at one domestic and one international conference.

5) Oct 2006 Obtain 5-10 nights of Keck AO time for the CATS program in Year 7. Complete Keck proposals for spring 2007. Submit another CATS science paper.

By end of Y8 (this has largely remained unchanged from our Year 5 proposal):

- ACS, Chandra, Spitzer, Galex, CFHTLS, and other data available for CATS fields.
- 15-30 laser guide star fields from Keck including an estimated 400-1000 galaxies.
- Laser Based AO system on Gemini (Altair) will be operational.
- Redshifts available for more of the AO targets.
- OSIRIS galaxy dissections (~20 galaxies total).
- Data in a community available database.

By end of CfAO 2nd term in late 2009 (changes from Year 5 proposal are in red):

- Laser guide star AO observations of >25% of GOODs North (~1000 galaxies). Given the planned shifts to new EGS, COSMOS, and GOODS-S fields since Year 5, the fraction is likely to be substantially smaller for GOODS-N. But the total areal coverage should be largely the same, about 40 square arc min. The number of predictged galaxies has been halved based on realistic estimates from actual observations.
- OSIRIS galaxy dissections (~100 galaxies).
- Clear demonstration to the community that AO can contribute in a complementary manner to much more expensive space missions in the study of the early Universe.

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5.7 Progress Report on Y6 CfAO funded Research: See co-PI proposals from Koo and Larkin

Current technical challenges and status.

1) Keck laser guide star system:

We have had spectacular success with our laser guide star time this year. The long-term success of CATS will rely on CARA providing a consistent and efficient laser guide star AO system on Keck. The LGS is needed to provide larger areal coverage in the very special HST fields that are part of the CATS program, and to gain experience in high-redshift science that links CATS to the science case for ELTs. For Fall 2005, Keck plans an intensive LGS AO campaign of roughly 30 nights. Of the UC allocation of roughly 10 nights, CATS was very fortunate to be awarded 4.5 nights or 45% of the total. Whether such amounts of LGS AO time will be available in future seasons for our Year 7 to Year 10 programs is as yet unknown. CATS can fortunately work with natural guide star AO as well, since its primary fields cover 5000 square arc min, large enough to provide plenty of natural guide star targets. By Year 9 of the CfAO it is likely that a new laser guide star will be available on the Keck I telescope.

2) PSF Characterization:

This is a challenge for both NGS and LGS AO. Progress is being made (see publications in the co-PI Koo proposal by CATS team members Steinbring and Faber and work in this area in the co-PI Larkin proposal). Until the Keck LGS system has been characterized more extensively and additional modes of operation are developed (e.g., wavefront sensor telemetry data during AO observations), the real-world utility of various PSF measurement methods will be developed and tested within the CATS program.

3) Parameter Error Analysis from AO Data:

Given the uncertainty and time variability of the PSF during AO observations, the effect on errors of derived parameters (e.g., fluxes for bulges or supernovae subcomponents embedded in a bright host galaxy, colors and radial light profiles from different AO images, astrometric positions of fuzzy objects) are not well known. We will improve our reduction and simulation software and library of AO PSFs to explore this issue. The knowledge and experience we gain here will be part of the legacy deliverables from the CATS program to the archive for the broad astronomical community.