CATS: Center for Adaptive Optics (CfAO - NSF Science & Technology Center) Treasury Survey of Distant Galaxies, Supernovae, and AGN’s

Keck 2 with Laser Guide Star (LGS)

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Image credit: Sarah Anderson/W. M. Keck Observatory 2002

CATS Website: http://www.astro.ucla.edu/~irlab/cats/index.shtml
**CATS: Center for Adaptive Optics (CfAO - NSF Science & Technology Center)** Treasury Survey of Distant Galaxies, Supernovae, and AGN’s

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Outline:
1. What are the goals of CATS?
2. Recent results from CATS
3. Progress with stellar populations analysis of high-z AGN
4. MOAO works (on the testbed)!

Image credit: Sarah Anderson/W. M. Keck Observatory 2002

**CATS: MAIN COMPONENTS**

**SCIENCE MOTIVATION:** Enhanced NIR studies of the structural, chemical, star formation, and kinematic evolution of distant galaxy sub-components on sub-kpc scales, including bulges, disks, bars, super star forming knots, lensing-merger & interaction signatures, AGN’s, and supernovae (SN).

**SURVEY STRATEGY:** Highly leverage the expensive AO data by observing extremely well-studied HST *field* galaxy survey regions (e.g., GOODS, GEMS, and EGS) with high resolution Adaptive Optics (AO) imaging and spectroscopy in the near-IR. Thus far, CATS has observed with Keck 2 in both NGS AO & LGS AO mode about 30 pointings around 15 natural and tip/tilt guide stars covering ~15 square arcminutes.

**CfAO SERVICE:** Release science-quality Keck AO data to the extragalactic community (DR1: Spring 2007 - see CATS website for some releases).

AO in the Near-IR with 8-10m telescopes is especially valuable for the study of distant galaxies because:

1. excellent match of PSF FWHM between HST in optical and Keck AO in the near-IR (0.05")
2. many galaxy components have sub-kpc sizes ideal for AO (from redshift $z \sim 0.5$ to 5, 0.05" is about 300-400pc)
3. the well-studied optical regime is redshifted to NIR (e.g., $H\alpha$ is in the J,H,K bands at $z \sim 1, 1.5, \text{and } 2.2$)
4. NIR added to optical improves stellar population analyses
5. NIR data reduce the effects of any dust extinction
AO Challenges

AO work is still in the pioneering phase because:

1. **AO STARS:** Except for a few lucky targets within ~30” of bright stars or QSOs, typical targets and survey fields lack VERY bright stars (10-14 mag) for non-LGS AO. Even with the 18th mag limit for LGS AO, only 20%-30% of high galactic fields are accessible.

2. **PSF UNCERTAINTY:** PSFs vary significantly in time and across the FOV; new techniques and observing strategies for calibrating the PSF’s are still being explored. Effects on photometry, structure decomposition, and especially error estimates on extended sources still need work.

3. **LOW EFFICIENCY:** The useful imaging FOV of < 1’ for AO systems is tiny compared to what is now available in non-AO NIR imagers. Observing overheads are large (~50%).

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Main Scientific Drivers & Questions to be Tackled by CATS with Keck AO

• **Morphology Evolution:** How did galaxies change from their chaotic forms at high redshifts to their common Hubble forms today? Can we see the assemblage from small to large as predicted by the standard paradigm?

• **Bulge and Disk Evolution:** When and how did bulges form? Are they younger or older than disks? Did large disks form early or not? Did disks form inside out? What is the relationship between disk motions and that of its dark matter halo? What is their chemical evolution?

• **AGN Evolution:** How have bulges been growing relative to the size of supermassive black holes? What are the nature of hosts of AGNs? How common are mergers and interactions among AGN’s?

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Measuring colors of galaxy subcomponents...

- Resolution of adaptive optics images nearly matches optical HST (ACS), better than HST NIR with NIC3

Color composite images

V, I, H

V, I, K’

HST optical images degraded to match resolution of NIR images for aperture phot

Bulge and disk more prominent in higher resolution image!

With Keck LGS AO, CATS can observe ~20% of GOODS vs. ~1% with NGS AO. Thus ~1500 Targets in the ~300 sqarcmin is accessible in GOODS, GEMS, & EGS.

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PSF FWHM of Keck AO in Near IR Matches that of HST in Optical of ~ 0.1"

Sample 40”x 40” Keck2 LGS AO NIRC2 image (exp~1h) combined with VI HST ACS images (1 orb) of EGS field where HST NIC3 also exists.

HST 2.4m has 1/4 the diffraction resolution of the Keck 10m.

Steinbring et al 2005

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NIR view of some apparent Major Mergers in optical (rest UV) show companions to be of small stellar mass, possibly implying triggering of star formation due to the merger or interaction.

Barczys et al. 2006 (PhD thesis)
First Extragalactic Results from Keck LGS AO showing a Chandra Source in GOODS-South. AO image indicates 2 nuclei rather than a single nucleus split by a dust lane.

Weak $z = 0.42$ X-ray source $\log(L_x)=41.9$

K-band helps to resolve degeneracies in stellar populations models

Melbourne et al. 2005

CATS Website: http://www.astro.ucla.edu/~irlab/cats/index.shtml
Extragalactic Results from Keck LGS AO showing Two Chandra Sources in GOODS-South

Melbourne et al. 2005

Extragalactic Results from Keck LGS AO showing Two Chandra Sources in GOODS-South

Melbourne et al. 2005

Strong x-ray source
log(Lx)=43.5
z = 0.61

FOV~ 5.5” x 5.5”

Weak x-ray source
log(Lx)=41.9
z = 0.42

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Stellar Population Synthesis Models combining NIR (Keck AO) + Optical (HST) help distinguish between red systems that are **OLD** from those that are **YOUNG & DUSTY**.

Melbourne et al. 2005

Dry merger!

Bruzual and Charlot (2003) single burst models with solar metallicity

Stellar Population Synthesis Models
Combining IR (Keck AO) + Optical (HST) helps separate the effects of age, star formation histories, and metallicity.

Bruzual and Charlot (2003) single burst models with solar metallicity

Steinbring et al. 2005
Measuring colors of galaxy subcomponents...

HST V image

3.5 arcsec

with apertures

with apertures

single burst models

\[ 7.00 < \log(\text{AGE [YR]}) < 7.70 \]
\[ 7.70 < \log(\text{AGE [YR]}) < 8.00 \]
\[ 8.00 < \log(\text{AGE [YR]}) < 8.70 \]
\[ 8.70 < \log(\text{AGE [YR]}) < 9.00 \]
\[ 9.00 < \log(\text{AGE [YR]}) < 10.00 \]

dust $\tau = 0$

Stellar populations model fits are insensitive to SF history beyond a look-back time of 1 Gyr.

Broadband colors, even including rest-frame UV and IR, become insensitive to the type of star formation beyond 1-4 Gyr (Lilly 2005).

Fitting SSP’s can only distinguish between the presence or absence of recent star formation in the past Gyr, independent of dust extinction.
Merger theory of black hole feeding

- Major mergers may be associated with black hole growth (Di Matteo et al. 2005, Springel et al. 2005a, b, Hopkins et al. 2006).
- It is observed that the mass of a galactic bulge is proportional to the mass of the black hole (Magorrian 1998, Gebhardt 2000).
- Simulations indicate that a single physical process powers both events: **Gas funneled to the center of galaxies via mergers.**
- This supports the notion that **star formation is simultaneous with black hole growth**, as mergers of gas patches typically yield starbursts.
Age measurements of high-z AGN on the ~kpc scale may assist in explaining today’s M-σ relation

- AGN have solar to super-solar metallicity (Groves et al. 2006), enabling better age constraints independent of dust.

Questions addressable with HST+AO:
- Are AGN bulges systematically younger than non-active counterparts?
- Where is the star formation occurring in AGN at z ~ 1?
- Is black hole growth simultaneous with bulge growth at z ~ 1?
- Does AGN feedback quench star formation? What is the timescale for this process?
Chandra sources in GOODS-S

- CATS has completed three key pointings of Chandra sources in the GOODS field, revealing 9 AGN or starbursting galaxies
- ACS B, V, i, and z combined with Keck AO K’

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<th>Z</th>
<th>Z-type</th>
<th>Class</th>
<th>B</th>
<th>(AB)</th>
<th>Soft L_\text{X} (\text{ergs/s}) \times 10^{42}</th>
<th>Hard L_\text{X} (\text{ergs/s}) \times 10^{42}</th>
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- Spectroscopic redshifts from Szokoly et al 2004
- Photometric redshifts from Zheng et al. 2004
- Chandra 1Ms catalog: Rosati et al 2002, Giacconi et al 2002

HST + AO imagery - Jason Melbourne

CATS Website: http://www.astro.ucla.edu/~irlab/cats/index.shtml
Imagery Highlights

XID 83

z = 2.02

Residuals scaled to self

Residuals scaled to image

Image

CATS Website: http://www.astro.ucla.edu/~irlab/cats/index.shtml
Imagery Highlights II

XID 266

Residuals scaled to self

Residuals scaled to image

Image

z = 0.73

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Discovery of a flat age gradient in XID83, a Type I QSO at z = 2.02

- Disk and bulge possess similar levels of star formation - need to explore further

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The CfAO is invested in the future of AO: Wide-field deployable IFU systems (MOAO)

Current components of UCO/Lick MOAO testbed:
- 9 100x100 Hartmann wavefront sensors for 9 laser guide stars
- 3 768x768 actuator deformable mirrors
- 10-30 meter class telescope mock-up

Current capabilities:
- Single line-of-sight correction with tomographic analysis (MOAO)
- Ground layer Adaptive Optics (GLAO)
- Traditional adaptive optics (SCAO - 40% Strehl on axis)
- Multi-conjugate adaptive optics (MCAO)

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Open loop tomography experiment

This result is a demonstration of reasonable Strehl 42" from guide stars on a thirty-meter telescope with a bright guide star and no wind.
Summary

• IR fluxes in addition to optical colors (including rest-frame UC) provide additional constraints on age/dust/metallicity

• Improved resolution (0.1") in IR permits stellar populations analysis at the kiloparsec scale at intermediate redshifts (z ~ 0.5-2)

• Rest-frame IR probes stellar content, revealing that many apparently major mergers in the optical are actually minor

• Stellar age measurements in the bulges of AGN can reveal timescales of bulge growth and black hole feeding

• We think we understand how wide-field AO should be done on 10-30 meter class telescopes.

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