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# Adaptive Optics Views of the Hubble Deep Fields Final report on LLNL LDRD Project 03-ERD-002

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## **Auspices Statement**

This work was performed under the auspices of the U. S. Department of Energy (DOE) by the University of California, Lawrence Livermore National Laboratory (LLNL) under Contract No. W-7405-Eng-48. The project (03-ERD-002) was funded by the Laboratory Directed Research and Development Program at LLNL. This work was also partially supported by the National Science Foundation's Science and Technology Center for Adaptive Optics, managed by the University of California at Santa Cruz under cooperative agreement No. AST-9876783. Data presented herein were obtained at W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory and the Keck II adaptive optics system were made possible by generous financial support of the W.M. Keck Foundation. The authors extend special thanks to those of Hawaiian ancestry on whose sacred mountain we were privileged to be guests. Without their hospitality, these observations would not have been possible.

# **FY05 LDRD Final Report**

## **Adaptive Optics Views of the Hubble Deep Fields**

**LDRD Project Tracking Code: 03-ERD-002**

**Claire Max, Principal Investigator**

### **Abstract**

We used laser guide star adaptive optics at the Lick and Keck Observatories to study active galactic nuclei and galaxies, with emphasis on those in the early Universe. The goals were to observe large galaxies like our own Milky Way in the process of their initial assembly from sub-components, to identify central active galactic nuclei due to accreting black holes in galaxy cores, and to measure rates of star formation and evolution in galaxies. In the distant universe our focus was on the GOODS and GEMS fields (regions in the Northern and Southern sky that include the Hubble Deep Fields) as well as the Extended Groth Strip and COSMOS fields. Each of these parts of the sky has been intensively studied at multiple wavelengths by the Hubble Space Telescope, the Chandra X-Ray Observatory, the XMM Space Telescope, the Spitzer Space Telescope, and several ground-based telescopes including the Very Large Array radio interferometer, in order to gain an unbiased view of a significant statistical sample of galaxies in the early universe.

### **Introduction/Background**

Despite enormous advances in observational data from the ground and from space, in theoretical understanding of the physics of the early universe, and in powerful computer simulations, many of the most fundamental questions about the origin and evolution of galaxies remain unanswered:

- 1) How did galaxies form and evolve?
- 2) How did massive black holes in the centers of active galactic nuclei (AGNs) form and evolve?
- 3) How are the evolution of galaxies and their central black holes related to each other?

In addressing these questions, the ability to study the past directly by observing distant objects should be a major advantage. But this potential advantage has three practical problems:

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

The keys to progress have been the advent of bigger ground-based telescopes to detect fainter objects; the use of Hubble Space Telescope (HST) to resolve smaller scale features in galaxies; and the use of the near-infrared spectral region to probe the red-shifted optical light from young galaxies. With the development of adaptive optics on the largest ground-based telescopes such as Keck (LLNL was a major participant in the Keck adaptive optics system design and construction), for the first time we have tools to address all three of the above issues.

The 10-m diameter Keck telescope has the opportunity to provide unique data. Although HST has the advantage of having a darker sky background because it is above the atmosphere, HST's 2.4 m mirror provides images that are four times poorer in spatial resolution than the 10 m Keck Telescope, which is diffraction-limited in the near-IR with adaptive optics (AO). Space telescopes are not expected to exceed the infrared spatial resolution of ground-based telescopes in the foreseeable future. The Spitzer Space Telescope is only 0.8 m in diameter, and the James Webb Space Telescope (JWST) will be only 6.5 m diameter. Thus neither has superior spatial resolution to Keck in the near-IR. What is missing from all these surveys are near-infrared images at spatial resolutions comparable to the 0.05 arc sec achieved by HST in the optical. By using laser guide star AO on the Keck telescope, the project described here provides the scientific community with unique and valuable data in this near-infrared gap.

The original two Hubble Deep Fields were observed for an entire week with HST's visible-light camera, WFPC2, using discretionary time made available by the Director of the Space Telescope Science Institute. Rather than keeping the data "private" for the usual year-long period mandated by NASA, the data were made available to the whole community as soon as they were reduced. The result was a wildly successful flowering of scientific papers based on the Hubble

Deep Field data set (Livio, Fall, and Madau 1998). Because of the very long exposure time, the Hubble Deep Field discovered and characterized a large number of infant and adolescent galaxies, and clarified many issues about how young galaxies form and evolve. Among the surprises was the fact that many galaxies at redshift of  $\sim 1$  looked lumpy and disordered, as if they were still assembling themselves from smaller sub-components. Many other galaxies, though already fully formed, were in the midst of dramatic merger events. Dynamical computer simulations have shown that this sort of merger event greatly increases the accretion rate of matter onto the black holes thought to be resident in most galaxy cores.

This project has taken the next step, by carrying out an adaptive optics survey to observe specific regions of the sky. We began by observing in sections of the GOODS and GEMS deep fields, and in FY 04 added two more fields: COSMOS and the Extended Groth Strip. All of these regions are the subjects of intensive international observing projects that are carrying out very long exposures on HST in the optical, the Chandra and XMM x-ray space telescopes in X-rays, the Spitzer Space Telescope in the mid and far infrared, and some of the world's largest ground based telescopes. The goal is to gain a deep, multi-wavelength view of a large sample of galaxies in the early universe.

To shed further light on the above results in the distant universe, this project also undertook to observe some nearby active galaxies and mergers in far greater spatial detail. This was made possible because they are much closer to us. We report here on the results both of our distant galaxy work and of our studies on nearby galaxies and mergers.

## **Research Activities**

### 1.0 Distant Galaxies

One of our goals was to enhance the understanding of galaxy evolution. This LDRD project emphasized the study of active galactic nuclei (AGNs) and their role in the evolution of galaxies. AGNs are galaxies whose central black holes are being “fed” by accretion from surrounding material. The strong correlation between the mass of central black holes in galaxies and the velocity dispersion of a galaxy’s spheroidal component (Ferrarese & Merritt 2000, Gebhardt et al. 2000) has led to the hypothesis that a galaxy’s central black hole and its spheroid co-evolve over cosmic time by growing incrementally in repeated merger events. Of particular importance is the relation between mergers, central black holes, and star formation. The process of merger-

induced star formation can, in principle, provide dynamically disturbed gas to “feed” the central black hole, and the black hole in turn can provide negative feedback that expels gas and “uncovers” a previously embedded AGN (Hopkins et al. 2005). This is illustrated in Figure 1, after Hopkins and Hernquist (2006).

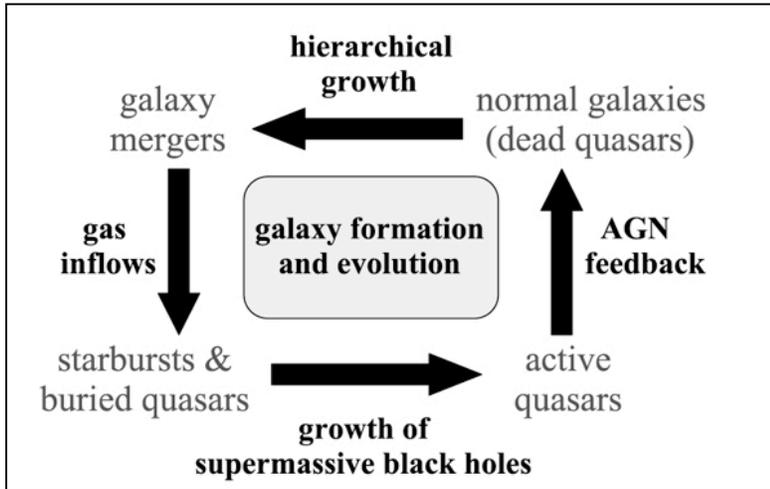


Figure 1. Schematic of the relationship between galaxy mergers, the growth of supermassive black holes in galaxy cores, and the feedback of active galactic nuclei (AGN) on the galaxies that they live in. After Hopkins and Hernquist (2006).

## 2.0 Nearby Active Galactic Nuclei and Galaxy Mergers

NGC 6240 (redshift  $z = 0.0243$ , distance = 98 Mpc, angular scale 1 arc sec on the sky = 470 pc) is a prototypical example of a merger of two massive disk galaxies. It contains two nuclei separated by 1.5 – 1.7 arc sec. In the optical through infrared, the angular separation between the two nuclei is known to decrease toward longer observing wavelength, suggesting heavy dust extinction in the nuclear regions. On larger spatial scales, the optical emission of NGC 6240 shows a dramatic “bow-tie” structure with tidal tails of the type seen in computer simulations of merging disk galaxies and observed in many other galaxy mergers (Figure 2). NGC 6240 has long been known from x-ray observations by the BeppoSax and ASCA satellites to contain at least one AGN, highly absorbed at x-ray wavelengths. In November 2002 it was announced (Komossa et al 2003) that Chandra high-energy x-ray observations have resolved two AGNs, one in each part of the dual nucleus, with approximately the same separation as the two compact nuclei seen at 5 GHz radio frequencies (Gallimore and Beswick 2004). Figure 2 shows the full NGC 6240 galaxy merger.

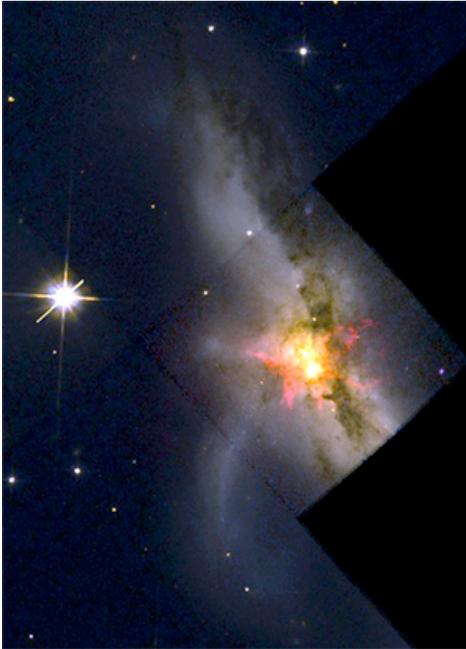


Figure 2. Zoomed-out HST image of the galaxy merger NGC 6240. The bow-tie shape and tidal tails are characteristic of merging gas-rich galaxies. The natural guide star is on the left, about 35 arc sec from the dual nucleus. Blue represents data from the F450W filter, red from F814W filter, green is average of these two filters. Superimposed in red is H $\alpha$  line emission (F673N filter), highlighting regions of most active star formation. The nuclear region which we studied in detail appears here as two adjacent yellow regions shaped like a slanted figure 8.

Because of the relative proximity of NGC 6240, the physical relationship between its stellar populations and gas can now be studied at high spatial resolution. One second of arc corresponds to 470 pc, so that scales smaller than 50 pc are probed using near infrared adaptive optics systems at the diffraction limit of a 10 m telescope. We have used the Keck adaptive optics system to image the central few hundred parsecs of NGC 6240. Figure 3 shows the two

nuclei; the length of the green arrow is one arc second (470 pc).

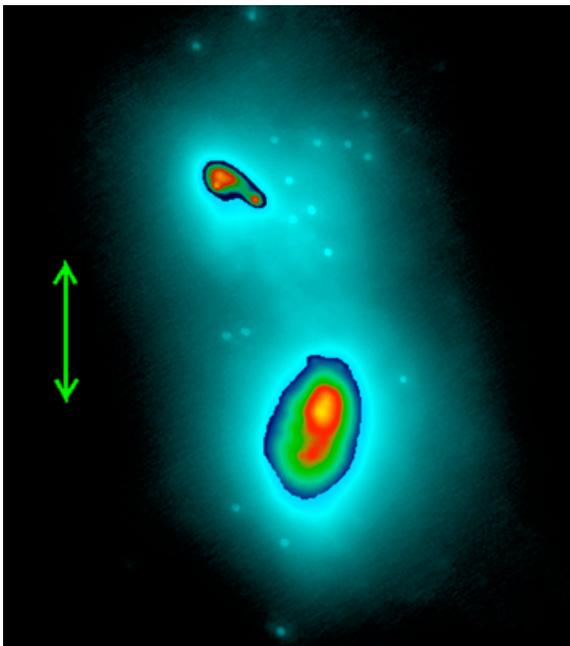


Figure 3. The dual nuclei of NGC 6240 seen with Keck adaptive optics, at a wavelength of 2.12 microns (K' band). The two nuclei (surrounded by dark blue), which appear monolithic in ground-based non-adaptive-optics images, are seen to have considerable substructure. In addition both are surrounded by many point sources that are young star clusters formed as a direct result of the merger. Here the two nuclei are shown in different color scales, so as to emphasize details internal to each nucleus.

We determined the age of the young star clusters (Pollack, Max, and Schneider 2006), as well as the exact location of the two black holes (one is in each nucleus).

## Results/Technical Outcome

### 1.0 Distant Galaxies.

#### 1.1 Stellar population-synthesis modeling

Computer simulations (e.g. Hopkins et al. 2005) suggest that galaxy mergers, rapid star formation, and black hole activity are causally connected. Keck K-band imaging and

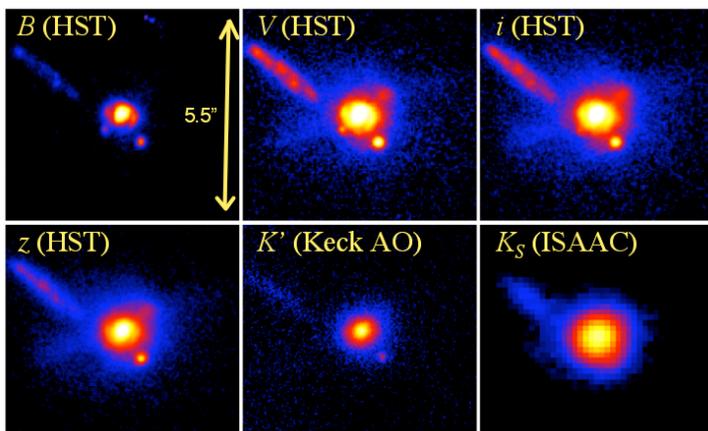


Figure 4. AGN XID-56 in the GOODS-South field, imaged by HST (B,V,i,z), Keck laser guide star AO (K' band), and VLT ISAAC (seeing-limited Ks band). This AGN has an optical-IR jet, as well as point-like substructure suggestive of a merger. The jet appears to point to the compact feature to the SW of the main nucleus. The Keck laser guide star image in the infrared K' band has spatial resolution comparable to HST at B and V, and superior to HST at i and z bands. (North is up; east is to the left in these images.)

photometry at resolutions comparable to those in Hubble B, V, i and z band images allowed us to do stellar population synthesis modeling of AGN host galaxies, and of the kpc-scale substructures within them, out to redshifts  $z \sim 1.5$ , to determine the relation between the age of the most recent starburst and the type of AGN activity observed.

We demonstrated that population synthesis modeling with data of this quality yields results of strong interest to galaxy and AGN evolution. For example in a paper published in ApJ Letters (Melbourne et al. 2005), we discussed one laser guide star field within GOODS-S that included two AGNs. Figure 4 shows one of the two AGNs, XID-56, in images ranging from B-band (Hubble) to K' band (Keck). The morphology of this object is disturbed and suggestive of an ongoing merger: 1) The core is fairly blue with several blue arcs surrounding the core, 2) An unresolved source in the SW corner is bright across the full wavelength range, 3) The semi-major axis of a very blue, linear structure suggestive of a jet (NE of the galaxy) points directly at the bright unresolved source (SW of the galaxy).

Figure 5 shows fluxes from aperture photometry centered on the bright nucleus of XID-56 (blue diamonds), with an aperture radius of  $0.2''$ . Over-plotted are several stellar population synthesis models: Bruzual and Charlot (2003) single burst models of various stellar ages and dust extinctions. The blue curve is a young (5 Myr) population, green is intermediate age (300 Myr), and red is an old stellar population (5 Gyr). Also plotted is a young (50 Myr) dusty (optical depth  $\tau = 5$ ) stellar population (brown curve) that best fits the optical HST data.

The models are normalized at a rest wavelength of  $5500\text{\AA}$ , which is redshifted into z band in

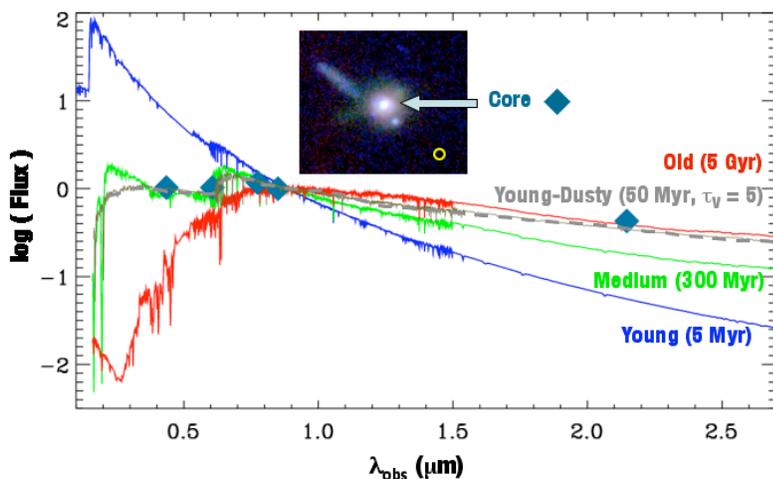


Figure 5. Blue diamonds: Aperture photometry centered on the nucleus of AGN XID-56. Colored lines: single-burst Bruzual and Charlot (2003) population synthesis models with different ages and dust extinctions. See text for details.

these data. The optical data are well fit by either the young dusty or the intermediate age stellar population. But the infrared Keck AO data point breaks the degeneracy of these models, indicating that the core of this galaxy is young and dusty.

Analysis tools of this kind have allowed us to do population synthesis modeling for the AGN host galaxies and mergers we observed, including their sub-components. With population synthesis we can determine whether the mergers we see are “wet” (gas-rich) or “dry” (gas-poor) (Bell 2004). For example we showed (Melbourne et al. 2005) that one of our AGNs has a double core; the colors of the two subcomponents correspond to those expected for a “dry” merger.

## 1.2 AGN morphology

Figure 6 illustrates the morphology of 10 distant AGNs in our sample observed with the Keck AO system in the 2.12 micron band ( $K'$ ). The accompanying table describes properties of these galaxies, including redshift ( $z$ ) and how it was determined (from spectroscopy or from photometric redshift information). With data such as this we are continuing to analyze the age of the stellar populations in the bulges and disks of our AGN sample, and to correlate the age with

properties of the nuclear activity as predicted by the models of Hopkins et al. (2005, 2006).

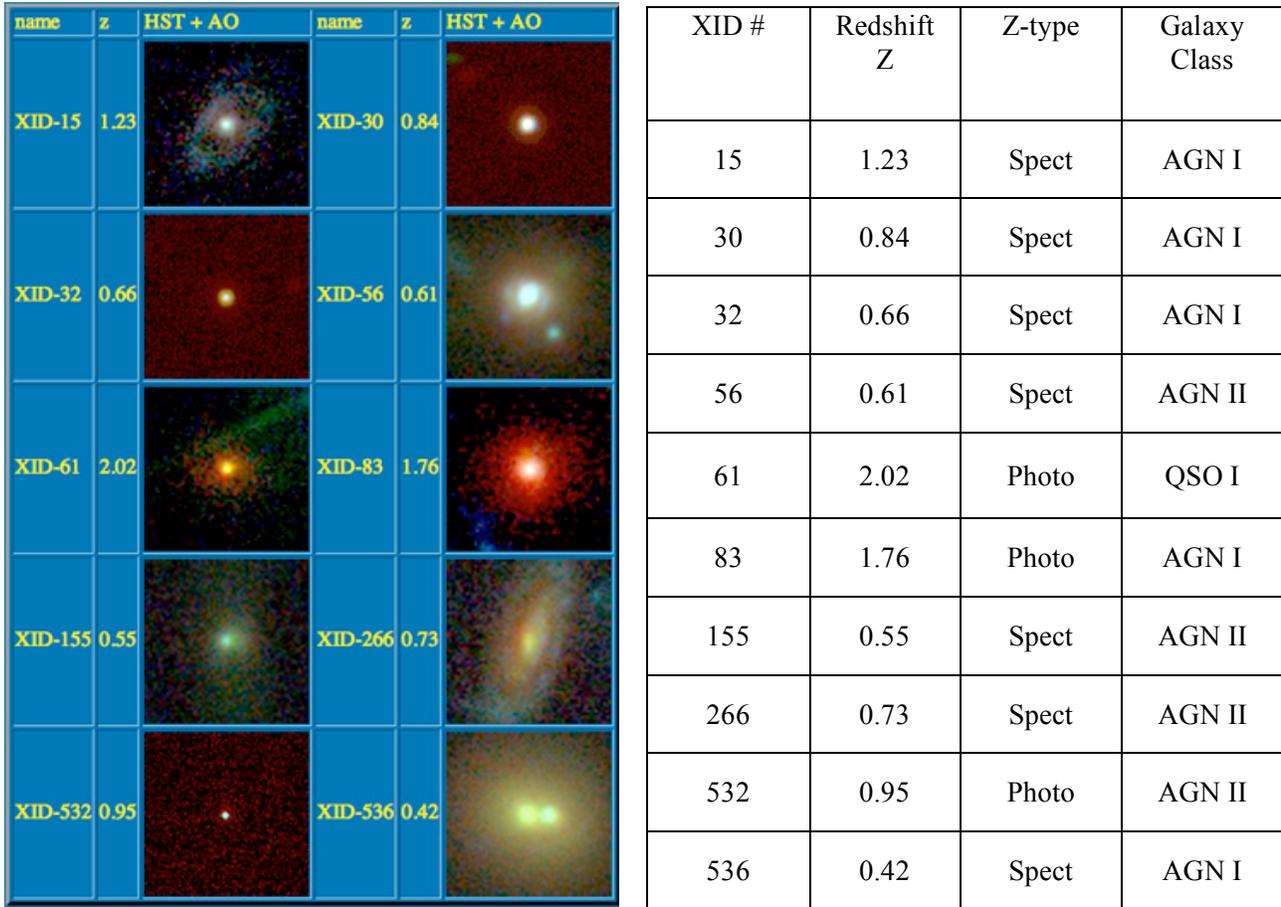


Figure 6 and Accompanying Table. Identification numbers (XID), redshifts, and images of 10 of the active galactic nuclei in our sample of distant galaxies.

### 1.3 CATS Data Archive

Data from HST, Chandra, XMM, radio telescopes, and the Spitzer Space Telescope on the deep fields (GOODS, GEMS, EGS, etc), obtained by groups around the world, are being made public as soon as they are satisfactorily reduced (see e.g. the GOODS web pages at

<http://www.stsci.edu/science/goods/>). To be useful to the whole community, our laser guide star AO data in the near-infrared must be made public as well, since their value lies in comparing and correlating features in the near-infrared with those at other wavelengths.

From the start of this project, we planned to build a public archive for our AO data (the first public archive of AO data, so far as we know). We have accumulated AO observations of many hundreds of galaxies. We called this the “CfAO Treasury Survey” (CATS), and this survey is continuing under the sponsorship of the Center for Adaptive Optics.

New PhD Jason Melbourne has done extensive work on what is required for the archive. This included discussions with individuals at the Space Telescope Science Institute who are responsible for the MAST archive, discussions with representatives of the National Virtual Observatory regarding archive format and standards, and discussions with members of the UC Observatories software group. In the spring of 2007 we plan the first full data release.

Figure 7 shows our Team web page, where Matthew Barcysz (recent PhD from UCLA) has posted Version 1.0 of the CATS data reductions.

**CATS Reductions - Version 1.0**

This is the second release of the reduced CATS imaging data. All imaging fields observed from 2003-10 to 2005-04 have been fully reduced, calibrated and are linked below. The images have these characteristics:

- Units are DN/sec
- FITS headers have some info about the reduction
- Rotation so that North is Up
- Accurate WCS info in FITS headers
- Best available photometric zeropoints in FITS headers

**Notes:**

- the table is sortable – just click on any of the column headings to sort by that column. This does not work properly with the Mac Safari browser. I'm not sure why...
- all jpg's are displayed with the same scale, from -0.3 to 0.3 DN/sec

Field	Files	Quad	Band	Date	AO	Minutes	Notes
ACS -0807+2113	<a href="#">FITS</a> <a href="#">JPG</a>	NE	J	2005-01	NGS	48	align w/headers only – looks okay
ACS -0807+2113	<a href="#">FITS</a> <a href="#">JPG</a>	NE	K'	2005-01	NGS	56	align w/headers only – looks okay
ACS 044 A	<a href="#">FITS</a> <a href="#">JPG</a>	NW	K'	2004-01	NGS	44	preslit was in and vignetting, won't be able to calibrate...
ACS 524	<a href="#">FITS</a> <a href="#">JPG</a>	SW	K'	2003-10	NGS	56	pretty good correction, big local galaxy!
ACS 524	<a href="#">FITS</a> <a href="#">JPG</a>	SW	K'	2004-01	NGS	66	pretty good correction, big local galaxy!
ACS 585 A	<a href="#">FITS</a> <a href="#">JPG</a>	NE	K'	2003-10	NGS	94	okay correction, bright GS w/ ghost affects bkg
ACS 585 A	<a href="#">FITS</a> <a href="#">JPG</a>	NE	K'	2004-01	NGS	90	poor correction, lots of objects
ACS 585 A	<a href="#">FITS</a> <a href="#">JPG</a>	SE	J	2005-01	NGS	52	okay, but fair bit of pattern noise

Figure 7. Team web page, with Version 1.0 of data reductions.

#### 1.4 Lick Observatory Survey of Nearby Active Galactic Nuclei

As preparation for our CATS survey of distant galaxies, we used the laser guide star adaptive optics system at UC’s Lick Observatory in a survey of a dozen nearby active galactic nuclei in

three near-infrared wavelength bands: K, H, and J. To accomplish this we also performed several upgrades of the Lick instrumentation. After obtaining high resolution images of each galaxy, we fit the brightness distribution with smooth Sérsic profiles and plotted the residuals (actual image minus smoothed profile-fit) in order to highlight galactic structures interior within 1 kpc of the galaxy’s center. Figure 8 shows typical results for two galaxies in the sample; in this case each has spiral structure (right hand panels) interior to 1 kpc. It has been hypothesized that inner spirals of this kind may be responsible for feeding gas onto the black hole accretion disk, enabling a central black hole to enter an “active” phase.

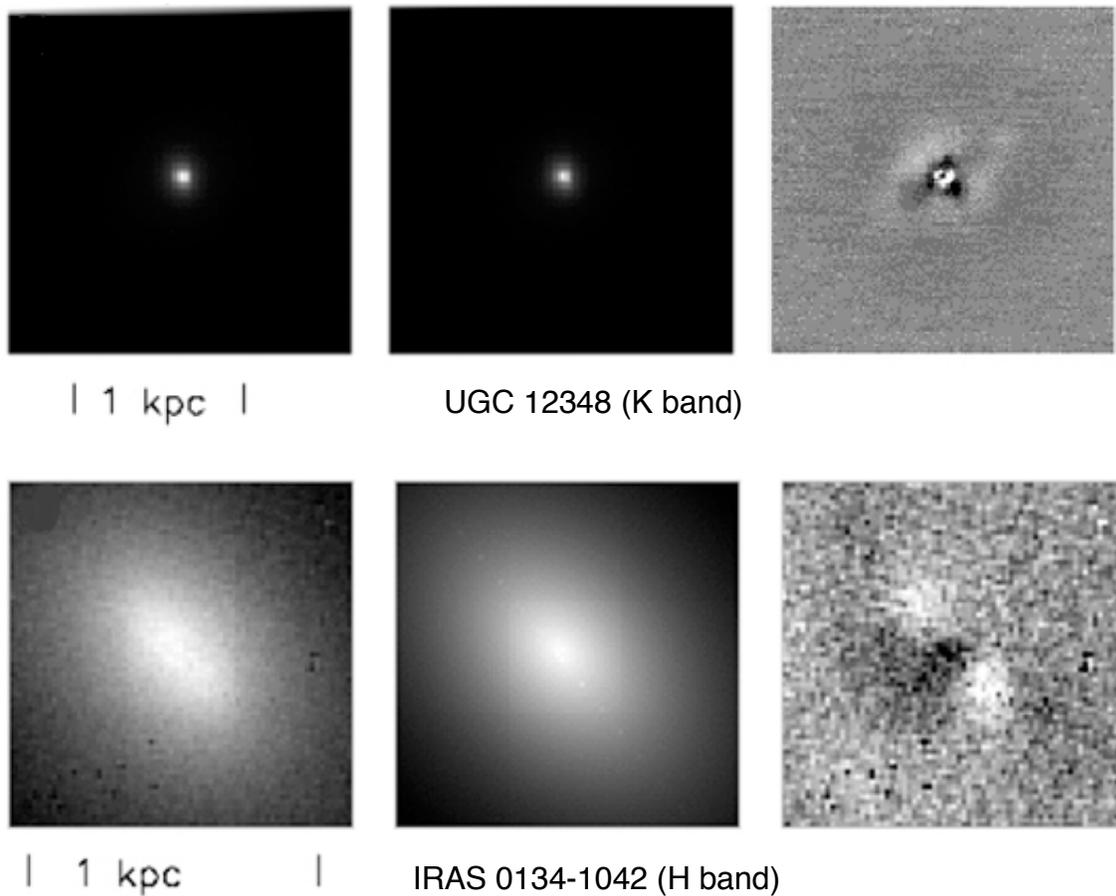


Figure 8. Brightness profiles and interior structure of two nearby active galaxies. Left panels: observations. Central panel: smooth model fit. Right panel: residuals (observations minus model) showing structure interior to 1 kpc.

## 2.0 Nearby Active Galactic Nuclei and Galaxy Mergers

We illustrate some results of our work on nearby galaxy mergers with a discussion of the age of the nuclear star clusters in NGC 6240, a merger containing two active galactic nuclei (Figs. 2 and 3). The small dots shown in Figure 3 are each a young star cluster formed in the course of the merger, as the interstellar gas in the two galaxies crashed together and new stars formed in the regions of enhanced density. In Pollack Max and Schneider (2006), we used stellar population synthesis models (similar to those described in Figure 5 for more distant galaxies) to determine the cluster ages. We were particularly interested in the question of whether the clusters formed in the most recent encounter of the two nuclei, or whether they were left over from a previous close approach (which would have taken place more than 100 million years previously).

Figure 9 shows the positions of the 32 star clusters whose ages we analyzed (red dots), superimposed on a greyscale image of the galaxy merger. We found that 27 of the 32 newly discovered clusters are consistent with being 15 Myr old, and 4 of the 32 clusters are probably between 3 and 15 Myr old. This means that the clusters were formed during the most recent encounter of the two nuclei, rather than in a previous pass. We were also able to characterize the amount of dust extinction at the position of the newly formed star clusters.

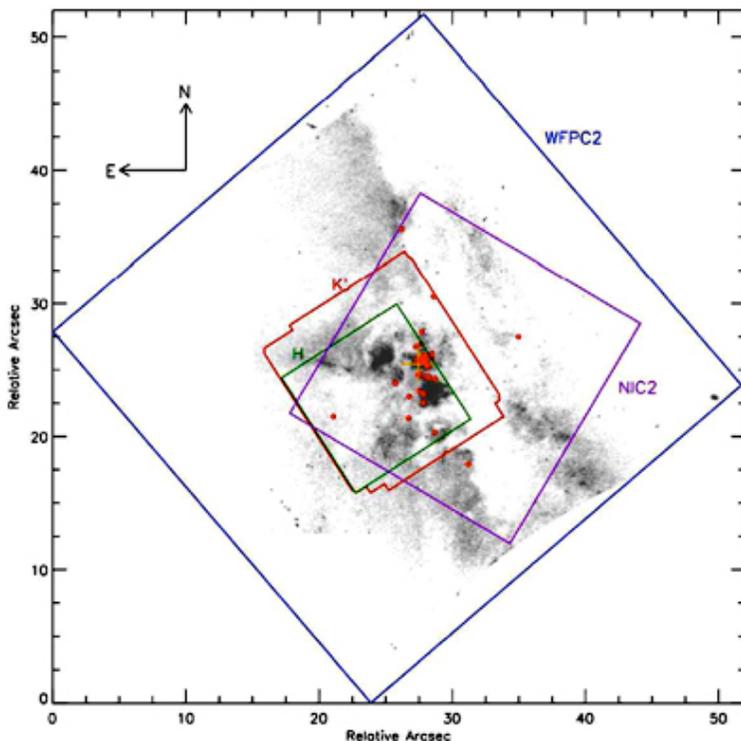


Figure 9. Star clusters in NGC 6240. The blue square shows the HST WFPC2 Planetary Camera field of view (F450W and F814W filters). The purple square shows the HST NICMOS NIC2 field of view (F110W, F160W, and F222M filters). The red and green squares show the Keck AO NIRC2 field of view (K' and H filters, respectively). Red dots show locations of 32 clusters whose ages we analyzed. Orange cross marks the location of the northern black hole. The overlaid grayscale image was taken in visible light with the HST WFPC2 F450W filter.

In a separate paper (Canalizo et al. 2003) we showed that the bright double-lobed radio galaxy Cygnus A has a remnant of a previous minor merger in its nucleus, and we speculated that this older merger remnant may be responsible for the observed accretion onto the central black hole in this active galactic nucleus.

### **Exit Plan**

This project is continuing under the auspices of the Center for Adaptive Optics, a National Science Foundation Science and Technology Center. The Center's headquarters is at UC Santa Cruz, and LLNL is a major Center participant.

### **Summary**

The Keck and Lick Observatory laser guide star adaptive optics systems, which LLNL was a major participant in designing and building, have allowed us to study some key issues in the formation and evolution of galaxies. We addressed the recent hypothesis that mergers between galaxies are what initiates black hole accretion activity in galaxy cores, by observing fields that had been deeply imaged by the Hubble Space Telescope, the Chandra and XMM x-ray observatories, the Spitzer infrared space telescope, and ground-based facilities such as the Very Large Array radio telescope in New Mexico. We used the laser guide star system at Lick Observatory to conduct a pilot survey of active galactic nuclei. We measured the ages of young star clusters formed in the course of a nearby merger between two disk galaxies (NGC 6240), and we discovered that a minor merger remnant may be what is causing accretion activity in the core of Cygnus A, a prominent nearby radio galaxy. Our data will be placed in a publicly available archive so that they can be easily compared with data from the myriad of other observatories that are studying these deep fields.

## **Acknowledgements**

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