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TITLE OF PROPOSED PROJECT: **MRI: Development of Enhanced Adaptive Optics System and Infrared Instrumentation for the Shane 3-meter Telescope**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 2,000,000	36 months	10/01/09	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
- ☐ BEGINNING INVESTIGATOR (GPG I.G.2)
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- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
- ☐ HISTORIC PLACES (GPG II.C.2.j)
- ☐ EAGER* (GPG II.D.2) ☐ RAPID** (GPG II.D.1)
- ☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ________ PHS Animal Welfare Assurance Number ________
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PI/PD DEPARTMENT: UCO/Lick Observatory

PI/PD POSTAL ADDRESS:
1156 High Street

Santa Cruz, CA 950641077
United States

PI/PD FAX NUMBER: 831-459-5717

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME Donald T Gavel	PhD	1988	831-459-5464	gavel@ucolick.org
CO-PI/PD Claire E Max	PhD	1972	831-459-5592	max@ucolick.org
CO-PI/PD Constance M Rockosi	PhD	2001	831-459-5246	crockosi@ucolick.org
CO-PI/PD				
CO-PI/PD				

Electronic Signature

CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the Authorized Organizational Representative or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), nondiscrimination, and flood hazard insurance (when applicable) as set forth in the NSF Proposal & Award Policies & Procedures Guide, Part I: the Grant Proposal Guide (GPG) (NSF 09-1). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

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In addition, if the applicant institution employs more than fifty persons, by electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of the NSF Proposal & Award Policies & Procedures Guide, Part II, Award & Administration Guide (AAG) Chapter IV.A; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be dislosed to NSF.

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The following certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

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The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

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Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:

(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant located in FEMA-designated special flood hazard areas is certifying that adequate flood insurance has been or will be obtained in the following situations:

(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
(2) for other NSF Grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE		SIGNATURE	DATE
NAME Sharon Collum		Electronic Signature	Jan 22 2009 7:55PM
TELEPHONE NUMBER 831-459-1378	ELECTRONIC MAIL ADDRESS slcollum@ucsc.edu		FAX NUMBER 831-459-4989

* EAGER - EArly-concept Grants for Exploratory Research
** RAPID - Grants for Rapid Response Research

MRI: Development of a high-performance adaptive optics system and camera for the Lick Observatory 3-m telescope

Project Summary

This proposal requests funding to develop a new, highly capable Laser Guide Star Adaptive Optics (LGS AO) system for the Lick Observatory 3-m telescope. The current 3-m LGS AO system was the first such system built for routine use in astronomy research and was the prototype for the extremely successful Keck Observatory LGS AO system. The new system will improved the delivered Strehl in J, H, and K bands by more than a factor of two, give significant Strehl into the optical, and improve the point source sensitivity by more than an order of magnitude. There is a large, established AO user group within the University of California astronomy community with science programs ranging from solar system studies of planets and asteroids to the morphologies of distant galaxies hosting QSOs. All benefit greatly from the proposed upgrade, and the enhanced capabilities will enable substantial new science programs.

Intellectual Merit: In recent years the UC Santa Cruz Laboratory for Adaptive Optics (LAO) has partnered with industry to develop and test micro-electromechanical (MEMS) technology deformable mirrors, which are now commercially available. In 2007-8 the first MEMS based astronomical AO system was built at the LSO and commissioned at the Lick Observatory 1m telescope. This proposal is to build a new LGS AO system at the 3m Shane Telescope using a similar new technology MEMS deformable mirror and a new laser guide star. The new laser is designed to enhance guide star signal return from the mesospheric sodium, and is presently operating at the Lawrence Livermore National Laboratory. At the same time, the infrared detector in the science camera/spectrometer used behind the AO system will be replaced. This new detector will have a plate scale that takes advantage of the diffraction limit down to J band and will have significantly higher quantum efficiency.

Broader Impact: This work has broader impact in several areas. This AO system will be a pathfinder for enhanced AO systems throughout the world. The MEMS-based AO system described in this proposal will incorporate the key new technologies that are baseline for the ambitious "Next Generation Adaptive Optics" system current in the design phase for the Keck Observatory.

This project is the right scope and schedule to allow important contributions to made by undergraduate and graduate students, and postdocs. The LAO has an outstanding record of training students and postdocs in the areas of optical and precision mechanical design, control systems and precision measurement. Students from the astronomy program, physics and engineering are part of the LAO. This is an ideal project in which this training can be carried out. The Lick Observatory is the primary astronomy research training ground for students in the University of California ten-campus system. This new system will give students increased access to premier AO science facilities similar to those at the world's largest telescopes. On the 3m, the students can lead proposals and will obtain hands-on AO observing experience.

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For font size and page formatting specifications, see GPG section II.B.2.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Project Description

1. Research Activities

Introduction. This proposal describes a new adaptive optics system on the Shane 3m telescope at Lick Observatory, achieved by upgrading the major components of the existing system: laser guide star, deformable mirror and science camera. The new facility builds on the science accomplishments and operations experience of the existing 3m AO system, the technology development done at the University of California Observatories (UCO) Laboratory for Adaptive Optics, and the experience gained from the ViLLaGEs project (Visible Light Adaptive Optics Experiments) on the Nickel 1m at Lick. With the proposed deformable mirror and laser, new system will deliver peak Strehl of (0.4, 0.6, 0.7) in (J,H,K), factors of two to five improvement over the existing system, and significant Strehl in red end of the visible spectrum. In tandem with improvements to the imaging spectrometer now in use with the AO system, the science reach of the new facility will be greatly enhanced with more than an order of magnitude decrease in the time required to reach a given signal-to-noise.

Figure 1. Lick Observatory 3-meter with laser guide star system in operation

At Lick Observatory we have pioneered the use of adaptive optics (AO) for astronomy for almost two decades. In collaboration with Lawrence Livermore National Lab, the first AO system put in regular use for astronomical observations was built for and commissioned on the Lick Observatory 3-meter telescope. The first sodium laser guide star (LGS) for astronomy use was implemented at the 3m in 1996. The Lick 3-meter LGS AO system was the basis of the very successful system built for the Keck Observatory. Despite the fact that it was developed largely as a prototype and proof of concept for the Keck system, the Lick Observatory AO system has provided the data for 21 science journal publications, second only to the Keck Observatory, ranging from studies of asteroid shapes and clouds on Nepture to morphologies of host galaxies of quasars.

Results from prior NSF support: In the last five years, largely through work at the UC Santa Cruz Laboratory for Adaptive Optics, we have continued to spearhead advances in AO. In 2007/8 we designed, built and commissioned at the Lick Observatory 1m telescope the first AO system with a MEMS deformable mirror, ViLLaGEs. This experiment implemented a 140 actuator Boston Micro Machines DM and demonstrated the "open loop" control mode for these devices (Gavel, SPIE 7015, 2008). We are proposing to build on this experiment and to implement a similar system at the 3-meter telescope and dramatically improve the performance of the AO system there. A significant part of the ViLLaGEs program was funded by NSF grant #0649261 ("*MEMS-AO/VILLAGES, MEMS in Astronomical Adaptive Optics Visible Light Laser Guidestar Experiments*," $200k, September 2006-August 2008) and this proposal leverages that work. The ViLLaGEs experiment is also a pathfinder for the Next Generation AO system at the Keck Observatory, and we expect to apply our experience with the new 3m AO system to future Keck facilities.

Lick Observatory AO Science programs. Lick Observatory is located at an elevation of 4200 feet atop Mt Hamilton east of San Jose. Time is assigned competitively with astronomers from all of the University of California (UC) 10 campuses and the associated labs (Lawrence Livermore National Lab, Lawrence Berkeley National Lab and the UC Berkeley Space Sciences Lab) eligible to apply. Through collaborations with other astronomers world-wide and including postdocs and graduate students in the UC system, Lick Observatory telescopes are available to a significant fraction of the US astronomical community. As we have completed the infrastructure to allow remote observations at Lick Observatory using stations at most of the UC campuses, the oversubscription rate on the 3-meter telescope is increasing. The site generally enjoys clear weather from May through November with good image quality. The location near to San Francisco Bay area communities has led to increasingly compromised sky brightness in the optical bandpasses, but for $\lambda>800$nm, the sky at Mt Hamilton is as dark as the best sites in the world.

The 3-meter telescope diffraction limit is $\lambda(\mu)\times 0.07''$. At 1μ this is approximately an order of magnitude higher spatial resolution than delivered by the uncorrected atmosphere at the best ground-based sites. For point sources and background-limited observations (the norm at wavelengths longer than 1μ) the gains in sensitivity scale as the image size squared. There are a large number of science programs that have been built around imaging at this spatial resolution and obtaining spectra in the near-IR with very significantly reduced sky background based on the use of narrower slits in an AO-corrected focal plane. The 3-meter AO system is in regularly use and has produced a number of interesting science results. In the Solar System, this resolution is sufficient to determine directly the shapes and rotation axes of asteroids and the incidence of binary asteroid systems (Marchis et al. 2003, Drummond et al. 2008) and to carry out spatially-resolved studies of the surfaces of planets and the larger moons (e.g. Roe et al. 2001). Other studies to date with the 3-meter AO system have been surveys for multiplicity among low-mass stars and stars known to harbor planets (Patience et al. 2002, Marcy et al. 2001, Burgasser et al. 2005), morphological studies of AGN and QSO host galaxies (Lacy et al. 2002, 2006), the environments of ULIRGs (Laag et al. 2006) and the centers of late-time galaxy collision remnants (Bogdanovic et al. 2003).

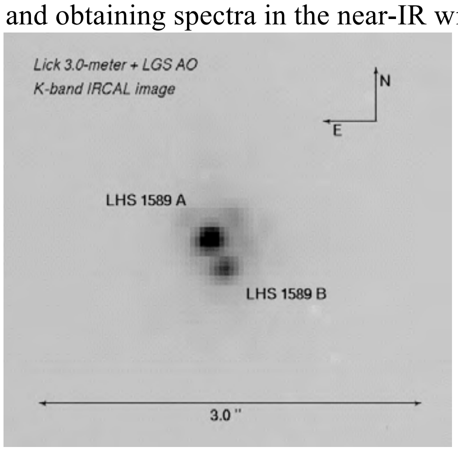


Figure 2. Discovery of a faint companion to the low-mass metal-poor star LHS 1589. Lepine et al. 2007. IRCAL and

The current AO system at Lick Observatory was developed in the early 1990s and, although a pioneer system and state of the art for many years, there are limitations in delivered Strehl and in the IR detector in IRCAL, the AO science camera, is several generations old. With the improved capabilities described in this program we believe the already high demand will go even higher and even anticipate some programs now carried out on the Keck system will be moved to the 3-meter.

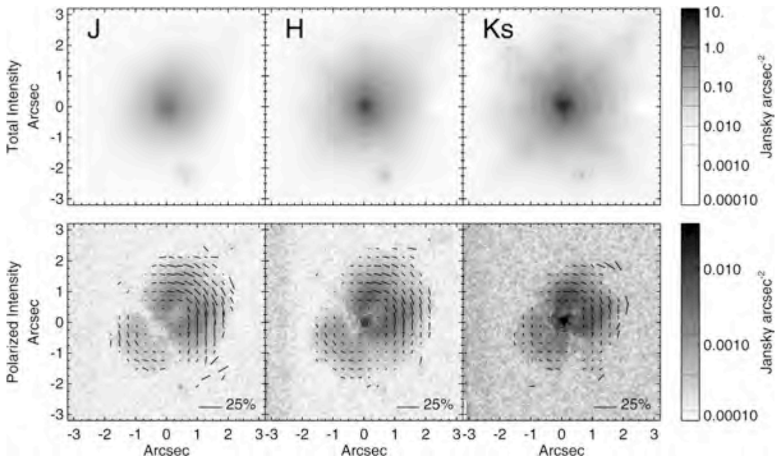


Figure 3. Discovery of bi-polar nebula in polarized light using IRCAL and 3m AO. Perrin, et al. 2008.

The improved science reach for the new AO system comes from the increased throughput, higher Strehl and better camera focal plane sampling. All of the current programs will benefit greatly and new programs will now be possible. As discussed elsewhere, the astronomy community that has access to Lick Observatory is large and the science interests very broad. We discuss here a few example science programs, but this is by no means a complete list.

For point sources, the expected sensitivity gain will reduce the time to a reach a given S/N at fixed magnitude by factors of 18,16,11.5 in J,H,K bands. Equivalently, the system brings within reach targets that have correspondingly smaller fluxes. For fixed luminosity limit, as for investigations of binarity fractions in nearby stars as a function of spectral type (e.g., Goldman et al. 2008), the increase in sensitivity corresponds to an increase in the available sample volume by a factor of 8 (H band). For proper motion studies, the sensitivity improvements increase the number of objects available in each field.

Studies extended sources will also benefit from the upgrade. The improved Strehl will enable morphological classification to fainter magnitudes and of smaller galaxies, and detailed studies of debris disk and other extended features around stars. High Strehl also reduces the background in regions close to bright point sources. Two examples where this latter feature is powerful, discussed in more detail in the following paragraphs, are studies of QSO host galaxies and identification of line-of-sight absorbing systems.

That there is a tight connection between central black holes and the properties of their host galaxies is quantified by correlations like the M_BH-sigma relation (e.g., Ferrarese & Merritt 2000, Gebhardt et al. 2000). How the black hole controls the evolution of its host galaxy to establish this relation is one of the major open questions of galaxy formation. There are many pieces to understanding where quasars fit in the evolution of galaxies over cosmic time: how the quasar phase is triggered, how the lifetime of the quasar phase relates to the growth rate of the black hole, whether and how energy from BH accretion couples to the gas in the rest of the galaxy to drive the AGN feedback mechanisms invoked by galaxy evolution models, and what observational consequences AGN feedback has for the morphology and star formation rate of their host galaxies. The enormous database of known QSOs from surveys like the SDSS provides a great science opportunity using the improved sensitivity to undertake a systematic study of the properties of host galaxies of QSOs to address these questions.

A related observational problem is identification of the galaxies associated with QSO damped Lyman alpha absorption (DLA) systems. At low redshift ($z<1$) these systems have been shown (Chen & Lanzetta 2003), to be associated with star forming galaxies. The distribution of magnitude and surface brightnesses for the DLA galaxies is not well constained by existing observations, and the low metallicity values for low redshift DLAs (Kulkarni 2004) suggest that they might be low surface brightness or dwarf galaxies. DLAs are one of our only probes of the interstellar medium in high redshift galaxies, but in order to use that information we need low-redshift observations of the DLA galaxies to relate the gas-phase abundance measurements to luminosity, surface brightness, size and morphology.

Because a DLA line of sight intersects the absorbing galaxy where the baryons are in the disk and bulge, the starlight is likely to be concentrated at small projected distances from the QSO. Contamination from the QSO light raises the background and reduces the detection efficiency. As for the QSO host galaxies, the improvement in Strehl will lower the QSO contamination and enable detection of fainter DLA host galaxies. In a Gemini AO study of DLA systems at $z<0.5$, Chun et al. (2006) find likely candidates for the absorbing systems in all seven of their fields. The galaxies are faint, $L < 0.1L^*$, and have scale lengths <~ 1 kpc. Despite their small sizes, these galaxies are resolved at $z<0.5$ in diffraction-limited imaging on the 3m, so the detection limits are a function of both surface brightness and total magnitude. We impose a reasonable surface brightness limit at one magnitude fainter in magnitudes arcsec^2 than the surface brightness of the QSO host galaxy measured to 30% by Lacy et al. (2002) with the existing 3m AO system. This should be a worst-case estimate of the QSO contamination and does not account for the sensitivity gains from the new science detector. Using psf-convolved models of disk galaxies at $z<0.5$, we estimate a detection limit for these extended sources by scaling the point source sensitivity to account for the larger area, and therefore larger background uncertainty, in these resolved galaxies. We find that a search for DLA galaxies using the new 3m AO system should be able to detect and measure the structural properties of galaxies like those found by Chun et al. (2006) out to $z=0.3$.

2. Description of Research Instrumentation and Needs

The proposed new instrument will be located at the Shane 3-meter telescope, at the UCO/Lick Observatory on top of Mount Hamilton in California. It will be a facility class instrument available to the UC astronomy community and is expected to be one of the three premier instruments available at this telescope (the other two being visible light spectrographs). The subscription rate for the adaptive optics system with infrared spectrometer/imager is expected to be higher than present AO system, approximately 80-100 nights per year, or approximately 1/3 of the available observing time.

The new technologies that will enable the proposed system are the result of ongoing developments that make the next three years particularly timely for implementation on this intermediate size telescope. As the scale and reliability of components (deformable mirror, real-time controller, laser beacon) develops, and as systems prove themselves to be scientifically productive to the astronomy community, the next step will be to implement similarly improved systems on the worlds largest telescopes. The new adaptive optics components and techniques have already been proven with laboratory testbed experiments at the Laboratory for Adaptive Optics (part of the UCO laboratory system technology development facilities at the UC Santa Cruz campus) (Wilhelmsen et. al., 2006, and Laag et. al., 2008), and have been demonstrated with an experimental instrument on the one-meter telescope at Mount Hamilton (the Villages experiments: Gavel, SPIE 7015, 2008).

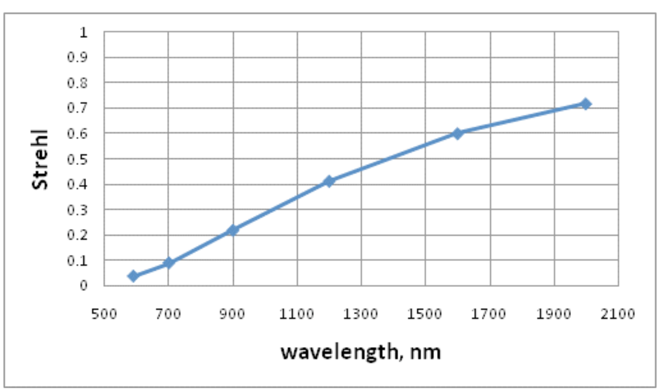


Figure 4. Modeled Strehl vs Wavelength performance of the new Shane telescope adaptive optics system.

The new system will provide significant improvements in performance in the following key areas:

Improved Strehl over a wider range of observational wavelength bands. Figure 4 shows the expected Strehl ratio as a function of wavelength. Improved Strehl in the proposed system is enabled by a higher-order adaptive optics system and brighter laser guide star. The Strehl ratio is an indicator of how much of the light from a point-like object lands in a diffraction-limited point-spread function in the focal plane of the instrument. It is a useful metric for detectability of point sources against a sky background, resolution of structures in extended-objects (e.g. galaxy structure or crowded stellar field), and contrast of dim sources next to bright ones (e.g. low mass companions to stars).

Increased sensitivity. The new system has increased sensitivity due to the improved image quality delivered by the AO system, the improved optical throughput with recently-developed high-reflectivity optical coatings, and higher quantum efficiency of the science detector. Overall science productivity of the new system is quantified by the exposure time needed to detect a certain brightness science target at a given signal-to-noise ratio. This is often expressed in terms of the speed or zero-point of the system. Table 1 shows that, with the expected improvements, the new system is anticipated to be at least 10 times faster than the present system. This is like feeding the present system with light from a primary mirror having 10 times greater collecting area, i.e. as if the Shane 3 meter telescope suddenly had a 10 meter diameter aperture. With this very large improvement in sensitivity, the science output is expected to increase dramatically.

Table 1. Comparison of point source sensitivities between proposed new system and current one.

Summary of performance, current system	*J-band*	*H-band*	*Ks-band*	
Throughput	16.6%	14.7%	16.9%	Top of atmosphere to detected photons
Sky and optics background	16.5	14.0	12.0	mag/band/arcsec^2
Point source sensitivity SNR=5, exposure = 300 sec	21.31	20.9	18.77	magnitude
Strehl	0.1	0.2	0.3	In typical seeing

Summary of performance, proposed new system	*J-band*	*H-band*	*Ks-band*	
Throughput	18.4%	20.3%	23.0%	Top of atmosphere to detected photons
Sky and optics background	16.5	14.0	12.2	mag/band/arcsec^2
Point source sensitivity SNR=5, exposure = 300 sec	22.93	22.49	20.1	magnitude
Strehl	0.4	0.6	0.7	In typical seeing

Speed improvement (exposure time to same SNR with same magnitude point source)	18	16	12	Times faster than current system

The new system consists of three basic subsystems: laser beacon generator, adaptive optics system, and the science camera. We describe each of these in turn below. In each of these cases, much of the present subsystem is reused, saving considerably on development cost. We highlight in each case what components are reused and what components are new. In the Management Plan we discuss our approach for minimizing the impact of system down-time in the observing schedule of the present working instrument. We note that all three subsystem replacements work together to bring about the sensitivity gain described above. In particular, to realize the full advantage of the increased actuator count of the new MEMS DM requires higher S/N sampling of the laser guide star on the wavefront sensor and consequently a brighter laser guide star. Similarly, to take full advantage of the improved Strehl in the camera focal plane requires the new detector with smaller pixels that provide Nyquist sampling at J band.

Laser Beacon Generator

The laser provides a guidestar in science target fields where no suitably bright natural guidestar is available. The use of a laser guidestar greatly increases the fraction of the sky over which adaptive optics is useful, from less than 0.1% to over 30%. The dye laser currently at the Shane was the first to be used in astronomy for regular science observations (Max et. al, Science, 1996). In order to achieve the anticipated higher Strehl and wider wavelength coverage, we will apply the knowledge we have gained in the past ten years about the physics of laser interaction with the sodium atom, and the advances in solid-state laser technology, packaged in a new 589 nm wavelength fiber laser. **The laser itself has already been developed under support from the NSF Science and Technology Center for Adaptive Optics (CfAO) (NSF award #AST-9876783, Nov 1999-Oct 2009) and the NSF Adaptive Optics Development Program (AODP)**, and is presently demonstrating it's high output power capability in the laboratory.

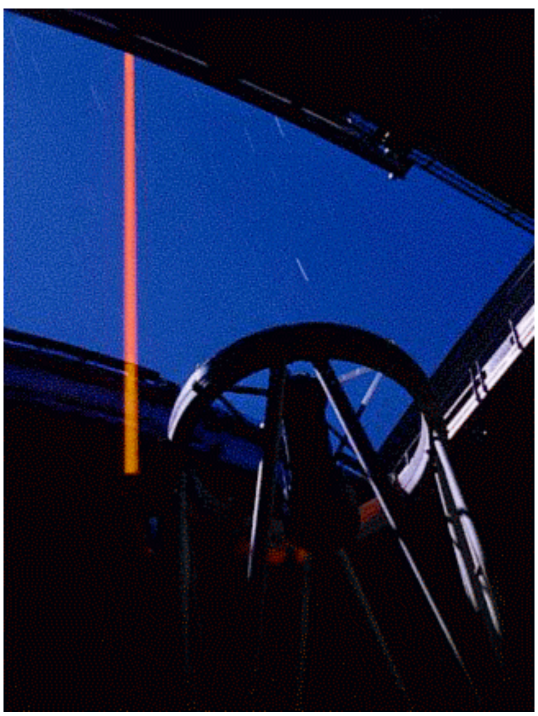
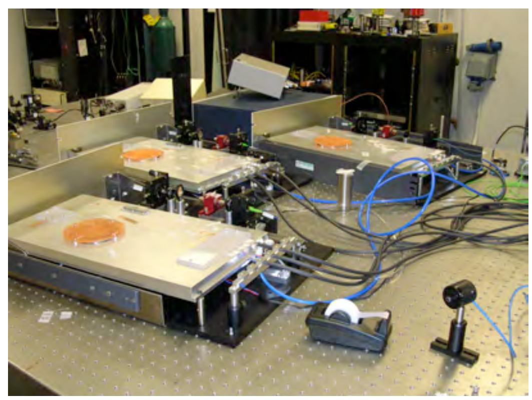


Figure 5. Laser beam launch from the side of the Shane telescope.



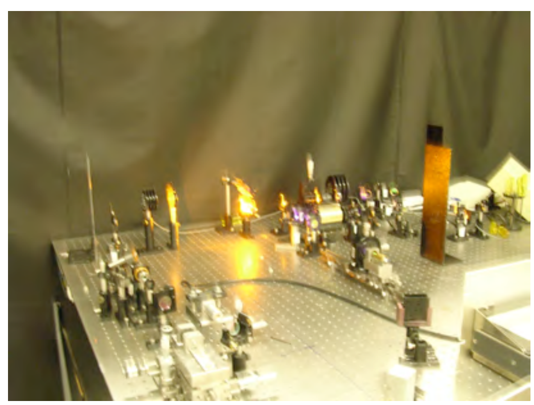


Figure 6. Top: High-power amplifier packages for the new LLNL fiber laser. Bottom: 589 nm output of the laser demonstrated in the lab.

Over the past two years the PI has under the auspices of the CfAO sponsored three workshops on Laser Technology and Systems for Astronomy, inviting experts from the fields of laser physics, atomic physics, adaptive optics, and astronomy. One of the major objectives has been to understand what laser pulse and spectral format will produce the optimum guidestar return signal per dollar spent on the laser. Breakthroughs have been made, enabled by the intense excitement generated by bringing together users, modelers, and builders of sodium guide star lasers. Experiments at the US Air Force Starfire Optical Range have so far demonstrated the best return using a narrow band CW laser (Denman et. al., SPIE 6272, 2006), although there are exciting prospects for intense pulsed lasers with precisely tuned multiple lines providing even brighter return efficiency.

Input from this community has spurred the development of the fiber laser. This compact solid-state laser has adjustable spectral and pulse formats, including a narrow-band CW option. Under the Villages program we plan to perform a series of experiments with it at the Nickel telescope to measure the return efficiency with various combinations of formats. The proposed Shane AO system can be operated in CW mode, and the performance budgets presented in this proposal are based on assuming the CW return efficiency that has already been demonstrated at Starfire.

The present Shane laser launch system uses a 30cm aperture refractive launch telescope mounted on the side of the telescope. This off-axis projection, one meter offset from the Shane's aperture, allows the signal return from the sodium layer to be sorted out from the background Rayleigh scatter of the lower atmosphere by using a simple field-stop in the wavefront sensor. At the base of the launch telescope there is a complete beam diagnostics system consisting of near and far-field beam profiler cameras and pointing and centering controls for the outgoing laser beam, including a high speed beam steering mirror for compensation of atmospheric and telescope jitter. The plan is to reuse the existing launch and diagnostics facility and simply replace the present laser input with a fiber-feed from the new solid-state laser.

Adaptive Optics System

Recent advances in microelectro-mechanical systems (MEMS) technology have led to the development of a new type of deformable mirror that is potentially a boon to astronomical adaptive optics. We propose to incorporate a 1024-actuator MEMS device (about 750 active actuators in the illuminated pupil) as the heart of the new system. The deformable mirror provides the active wavefront correction and is in the path of both the science light and the guidestar light. This large number of actuators enables excellent wavefront correction and leads to very high Strehl across the near- infrared bands with some decent performance in the shorter "visible" bands.

A schematic diagram of the adaptive optics system is shown in Figure 7. Incoming light from both the sodium guidestar and the science target is reflected off of the fast tip/tilt mirror and deformable mirror. Then, a dichroic beam splitter sends the guidestar wavelengths (both the laser line at 589 nm and the visible tip/tilt star light at 600—900 nm) to the wavefront and tip/tilt sensors, while the infrared science light proceeds on to the science camera. Signals from the wavefront sensor are used to drive the deformable mirror and fast tip/tilt mirror in a closed-loop control configuration.

The Center for Adaptive Optics and the Laboratory for Adaptive Optics have over the past 10 years been collaborating with MEMS manufacturers to perfect a device design that is suitable for astronomy (Gavel, SPIE 6467, 2007). This effort has paid off with a number of interesting devices now appearing on the market. For the Lick system, we plan to use the 32x32 device constructed by the Boston Micromachines Corporation. These devices are the result of years of perfecting a silicon micromachining process (Bifano et. al., SPIE 5553, 2004) for yield (percentage of working actuators), actuator displacement range, surface quality, and optical coating.

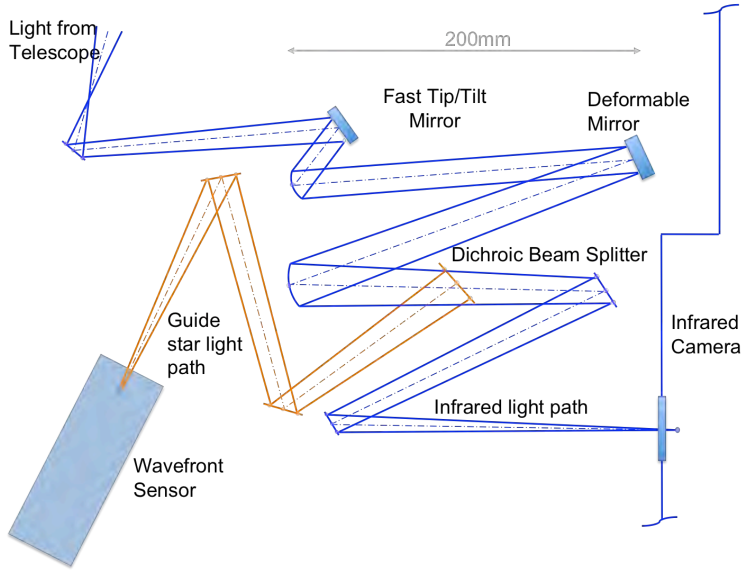


Figure 7. Representative layout of the adaptive optics system, drawn roughly self consistent in scale. The AO relay images the telescope pupil onto the MEMS deformable mirror. The very compact design is enabled by the small size of the MEMS device.

Since MEMS deformable mirrors, unlike the older technology piezo-actuated mirrors, have zero hysteresis, they can be commanded to fit the wavefront over any of the spatial frequency range up to the Nyquist limit without necessarily having the wavefront sensor sampling to support it. In the proposed system, the spatial frequencies can be controlled at up to 16 cycles per aperture (10 cm sample spacing across the 3-meter aperture) whereas the proposed wavefront sensor sampling measures up to 8 cycles per aperture (20 cm diameter subaperture). The reason for choosing a 32-across (1024 actuator) MEMS device is that these are what are now available commercially. There is a considerable development cost in designing and perfecting the manufacturing process for a new device, but once established, the per-unit cost is low. This particular device provides a reasonable size clear aperture for packaging the rest of the optical system around it and leaves an upgrade path for a future higher order wavefront sensor.

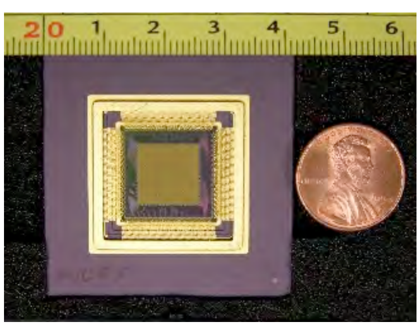


Figure 8. Photograph of one of the 1024 actuator MEMS deformable mirrors that have undergone testing at the Laboratory for Adaptive Optics.

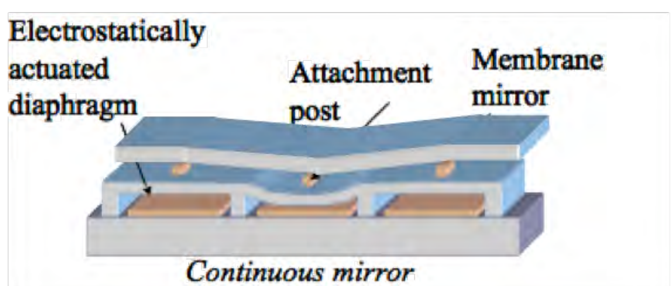


Figure 9. MEMS actuator details. An electrostatically deflected membrane is opposed by the membrane's tension restoring force. The reflective top sheet is attached to the actuator membranes by posts. Drawing courtesy Boston Micromachines Corporation.

With the luxury of repeatable go-to control of the DM, we have the option of optimizing the wavefront sensor sampling separately. The 20 cm diameter subaperture in the nominal design provides a balance in the error budget between sampling error and measurement noise at low flux per subaperture. This will provide wavefront data at up to 8 cycles per aperture. The repeatable go-to nature of the deformable mirror will allow 8-16 cycles per aperture to be controlled open-loop to either a zero setting, or to an offset to cancel internal aberrations, or to a dynamic value calculated with a predictive controller. All of the performance predictions (section below) are based on the most conservative of these options: that of zero command in the 8-16 cycle range. The choice of subaperture size is driven by the expected photon return of the laser guidestar. The 32 across DM gives the flexibility to increase the wavefront sensing by up to a factor of two if more laser output power is available, or for periods of enhanced seasonal sodium density.

The wavefront sensor is built around a 80x80 E2V CCD39 detector, packaged with SciMeasure camera drive electronics. This is the camera in the present AO system and it is not necessary to enhance or upgrade the sensor or electronics for this new system. The front end optics however will be modified to accommodate the increased sampling. Optically, it is a Shack-Hartmann sensor, with (in the new system) 16 subaperture across, each sampled at 4 pixels per subaperture on the detector, with no guard bands. The no-guard-band arrangement has proven successful in the Villages experiment given a properly sized and aligned field stop at the front end of the Hartmann sensor. This will effectively block stray light from adjacent subapertures from crossing and confusing a wavefront slope measurement in place of using valuable detector real estate to provide a buffer zone.

Science Camera

The infrared science camera for the new system will have imaging and a spectroscopy modes, built around a Hawaii RG architecture detector. The exact device (and whether is a Hawaii-1 or Hawaii-2 device) remains to be determined based on availability, however a new Hawaii-2 device from Teledyne Labs is accounted in our proposal cost estimate. The existing optical arrangement (Figure 8) in the IRCAL camera will be our working baseline, with the new detector simply put in place of the old PICNIC array now there.

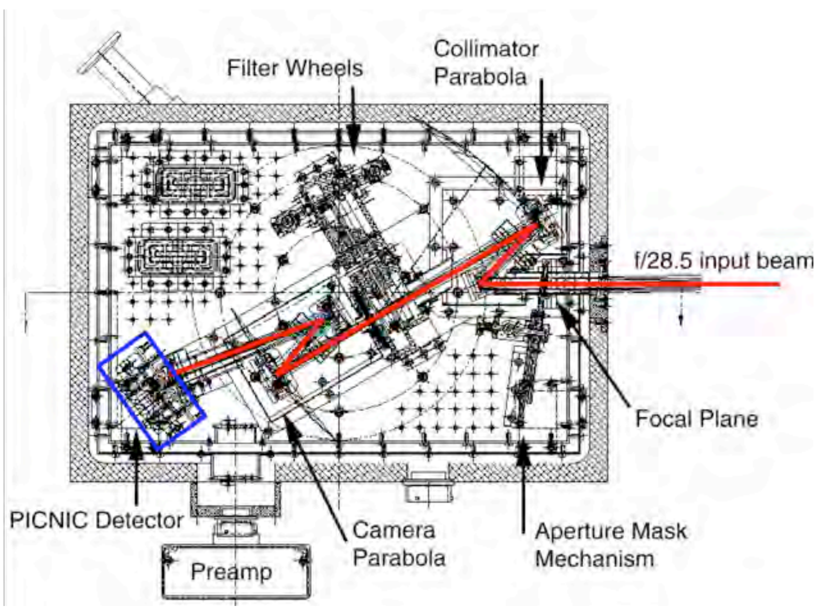


Figure 10. Optical layout of the IRCAL infrared camera and spectrograph.

The Hawaii array has roughly one half (18.5 micron vs 40 micron) the pixel size of the present PICNIC detector, which enables this new arrangement to now be Nyquist-sampled at the diffraction limit in all the near-infrared bands (roughly 35 milli-arcseconds per pixel). This is well matched to the higher Strehl and diffraction-limited resolution across the near-IR bands expected from the new adaptive optics system.

Table 2. Infrared science camera parameters

Observing Modes	Imaging, spectroscopy, polarimetry, coronagraphic
Focal plane array	Hawaii 1 or Hawaii 2 RG detector
Imaging plate scale	35 milliarcsec/pixel (80 mas is diffraction limit in J)
Imaging field of view	20 arcseconds
Spectroscopic resolution	R=700
Filter Set	J, H, Ks, (exchangeable, 2 wheels with 8 positions each)

The optical arrangement of IRCAL camera is shown schematically in Figure 10. The incoming infrared science light, converging at f/28.5, enters the vacuum enclosure through a window. This is re-imaged at f/33 on to the detector using an all-reflective off-axis parabola relay. A cold stop imaged to the telescope pupil is located in the collimated space between the parabolas. Two filter wheels are also located in the collimated space allowing a choice of band-pass filters, spectroscopy grisms, and a Wollaston prism for polarimetric observations. The incoming beam converges to a focus inside the enclosure where a spectroscope slit can be positioned. There is also an optional focal plane stop, which, in conjunction with a Lyot stop in one of the filter wheel positions, forms a coronagraphic capability.

This proposal calls for only the replacement of the detector and readout electronics, and for some mechanical refurbishment of the enclosure and cryogenic mechanisms. The enclosure containing the camera optics may need to be enlarged to accommodate the newer detector and its mount. Re-engineering the cryogenic mechanisms for the filter wheels, grisms, and stops will provide more modern and reliable versions that will enhance on-sky productivity.

Performance Predictions

Performance expectations were summarized in Figure 2 and Table 1. The Strehl predictions are base on a generic and well-established approach to wavefront error budget modeling (Gavel, Morris and Vernon, 1994). The sensitivity analysis is based on a detailed assessment of the transmissivity and thermal emission of all the optical surfaces in the proposed system, folded in with an understanding of the infrared sky brightness at the Mount Hamilton site.

Wavefront error and Strehl performance improvement in the proposed system is due increased return signal from the guidestar as enabled by the new laser technology and to the addition of more modes of wavefront correction enabled by the MEMS deformable mirror. These two trade with other error budget contributors (such as signal to noise in the wavefront sensor) to give an optimized system design. The major contributors to the error budget is shown in Table 3. A side by side listing of the present Lick AO system's error budget is provided for comparison.

Sensitivity (time to achieve a given signal to noise for a given brightness source) can be dramatically improved over uncorrected seeing by adaptive optics because point sources are sharpened and thus made much brighter against a uniform background. Unfortunately, AO introduces a large number of intermediate optical surfaces which, if not sufficiently reflective, can lose much of the signal gain to transmission loss and also be a source of background emission that degrades the infrared observation. We control these losses in the proposed system by utilizing an all-reflective relay design with enhanced broadband high reflectivity coatings. The common infrared science and laser guidestar paths will use an enhanced silver coating, developed at the UCO labs in Santa Cruz, that is extremely reflective in the IR bands (>96%) and has a tuned peak at 589 nm (99%), the laser guidestar wavelength. The infrared-only paths can utilize this or alternatively a pure gold coating.

Table 3. Wavefront and Tip/Tilt error budget for laser guide star operations, representative for good seeing conditions (r0=11 cm) at Mt Hamilton and a bright tip/tilt star.

Error Term	Proposed New System	Existing System at the Shane
Wavefront spatial sampling	72 nm	112 nm
Wavefront temporal control	46 nm	65 nm
Wavefront SNR (measurement)	40 nm	152 nm
Non-common path aberrations	30 nm	30 nm
Other calibration errors	40 nm	100 nm
Total Higher Order	106 nm	225 nm
Tip/Tilt residual from atmosphere	5 mas	5 mas
Tip/Tilt residual from telescope vibration*	20 mas	20 mas
Total Tip/Tilt residual	21 mas	21 mas

*Reduction of vibration disturbance is a separate ongoing program and we expect these values to improve over the next few years.

We chose not to cool the adaptive optics components for cost reasons and to avoid the additional transmissive loss in the windows. Even at dome temperature, the AO optics thermal emission is important at wavelengths longward of the Ks band, which are not targeted for this instrument's science case. The near-IR bands are instead dominated by OH emission lines in the sky glow. Thus signal to noise is improved directly by optimizing transmissivity of the optics and the quantum efficiency of the detector while reduction of the temperature of the optics only marginally improves it.

3. Impact on Research and Training Infrastructure

The AO system is one of the major scientific facilities on the 3m and one of a handful of operating laser guide star AO systems in the world. Through collaborations with other astronomers world-wide, and including postdocs and graduate students in the UC system, more than 500 astronomers have access to this facility at Lick Observatory. Therefore this new system will be a major addition to the US astronomy research infrastructure.

Mentoring Graduate Students. The AO expertise assembled at UCO/Lick make it one of only a few labs/observatories in the world capable of designing, building and commissioning a laser guide star AO system. As such, it has both the responsibility and capability to train students in engineering, astronomy and related departments as experimentalists. The link between the astronomy department and the UCSC Baskin School of engineering is strong; currently there are engineering students collaborating with the PI in the LAO. Five students participated in the Villages experiment that developed and tested the MEMS system for the 1-m. The Villages work is a significant component of the thesis work of two of those students. UC Santa Cruz sponsors the Bachmann graduate student fellowship, which previously supported one of the students work in the LAO. We expect to attract a new Bachmann fellow to participate in the new 3m AO project. Under PI and Co-I mentorship, there will be opportunities for students to take ownership of major roles on this project.

Mentoring Postdocs. The depth and experience of the technical staff and the critical mass of experimentalists on the research and teaching faculty also make UCO/Lick an good environment to mentor young experimentalists as project leads. We have included two such positions in our plan for the AO upgrade. One is the project scientist position who will work closely with proposal PI and Co-PIs as overall lead on the project. The second will work with Co-I Rockosi on the upgrade to the science camera. The position will be offered as a 3-year postdoctoral appointment, aimed at the junior level just after the PhD. The project plan includes 2/3 of that postdoc's time on the upgrade work, including commissioning and science testing. The remaining year will be funded by Co-I Rockosi along with the 2 years formally included in the cost sharing of this proposal, with the intent that the postdoc continue their research program. To that end, Rockosi will mentor the postdoc in starting collaborations, getting telescope time and data, and in balancing science and instrumentation. Both junior scientists may find themselves in the position of having to leave Lick Observatory to further their career before they have the opportunity to do science with the new AO system. There is an established precedent of the University of California time allocation committee giving researchers in that situation the opportunity to continue to apply for 3m time until the completion of their science projects. We will provide our junior colleagues with that same opportunity if the situation arises. The Bachmann fellow and the instrumentation postdoc will both be expected to participate in the ISEE program described below.

Approximately half of the UCSC and Lick Observatory personnel in this project will participate in programs of the Institute for Scientist and Engineer Educators (ISEE) at UCSC. This new organization is a spin-off of the education programs developed by NSF's Center for Adaptive Optics. ISEE's goal is to prepare science and engineering (S&E) graduate students for their educational role as future faculty members, and for a wide range of other science and engineering careers requiring teaching skills. UCSC science and engineering graduate students learn about curricular innovations in ISEE's unique "Teaching Labs," courses and co-curricular activities aimed at recruitment, retention, and advancement of students from diverse backgrounds. UCSC senior scientists and engineers participate as mentors and advisors for the students, with a particular role in introducing students to the type of engineering that is done in the active UC Observatory shops and in the Laboratory for Adaptive Optics. The core activities of ISEE are funded through internal sources at UCSC.

We have found during the almost 10 years of the CfAO that few undergraduates realize the crucial role played by electrical, mechanical, optical, and computer engineers in the functioning of astronomical observatories and instrumentation labs. UCSC senior scientists and engineers will participate as mentors and advisors for the college students served by ISEE's Teaching Labs, with a particular role in introducing undergraduates from under-represented groups to careers in engineering. This will be accomplished through exercises and examples in the Teaching Labs and through our engineer role-models at the UC Observatory shops and in UCSC's Laboratory for Adaptive Optics.

CfAO education programs, and by direct extension the new ISEE organization, have an excellent track record of recruiting undergraduates from under-represented groups to participate in Teaching Labs. In recent years, for example, CfAO education programs (via their Teaching Labs) have sent the first three Hispanic graduate students to UCSC's Baskin School of Engineering, where these students have thrived. We have established excellent working relationships with the regional community colleges, which serve a large Hispanic population; participants in our Teaching Labs are recruited at these institutions (among others). We know that ISEE's model will be a good one, because it is based upon the highly successful model developed in the CfAO. For example in the CfAO Internship Program, towards which many of our Teaching Labs have been focused to date, more than 80% of the students are still "on track" towards science or engineering careers (in S&E majors in college or grad school, or in S&E jobs in the workforce). Approximately 75% of the undergraduate participants in these programs were women or under-represented minorities.

The research scientists associated with the proposed AO project are all participants in ISEE, providing an excellent and already established vehicle for undergraduate student interns in the ISEE program to gain experience in a state of the art research and development project.

4. Management Plan

The program plan for the instrument extends over a three-year period. This is marked by milestones for preliminary design, final design, acquisition of crucial components, laboratory integration, and commissioning at the telescope. The management process draws upon the extensive experience of the UCO/Lick Observatory in designing and fielding large instruments for astronomy, including all of the major instruments at Mount Hamilton (Hamilton spectrograph, Kast spectrograph, etc.) and several large instruments for the Keck Telescope (DEIMOS, NIRC-II, ESI).

Management Structure. The PI, Dr. Donald Gavel, will direct the project with science oversight by Co-Is Professors Constance Rockosi and Claire Max. Dr. Gavel will manage adaptive Optics system development. David Cowley, director of the Lick Optical Shops will oversee opto-mechanical work for the refurbishment of the IRCAL camera. The management team will also include a PhD junior project scientist / project manager who under the tutelage of the PI, will have the opportunity to devote nearly full time to oversee the project and assist in its development and deployment.

Personnel. The UCO/Lick Observatory has a number of qualified engineers, programmers, technicians, and machinists well trained in the art of instrument building. For the AO portion of the proposed project the optical, mechanical, and computer engineers will be personnel who have already had experience with building AO systems (Villages).

In particular, Mark Reinig, who has over 20 years experience as an independent contractor in real-time embedded systems and has recently successfully deployed the Villages AO control system, will be the lead programmer for the real-time control system. Chris Lockwood, who has 8 years experience in designing advanced optomechanical systems for astronomical instruments, including the Keck Low-Resolution Spectrograph upgrade, the Keck Next Generation Adaptive Optics system and the Villages optical AO system, will be the lead opto-mechanical design engineer. PhD researcher Renate Kupke, who did her PhD research designing solar adaptive optics at the University of Hawaii in the famed Francois Roddier group, will lead the AO optical design effort.

The infrared camera work will be lead by David Cowley, who has extensive experience in leading development teams for both visible and infrared instruments, including the Keck DEIMOS and ESI spectrometers, the Keck Atmospheric Dispersion Corrector, and the Keck Low Resolution Spectrograph Red-Side upgrade, The Keck HIRES detector upgrade and a number of smaller projects in the last decade. The UCO/Lick Shops has considerable depth with 6 engineers, 4 electrical and mechanical technicians, and 5 machinists.

Mount Hamilton staff will be involved in the instrument design, deployment, and commissioning. Associate specialist Bryant Grigsby will aid in transitioning the operations and user interface portions of the AO system and IR camera from the current AO system to the new one. Bryant has considerable experience operating both the Lick AO system and the Villages AO system. Laser electro-optics technician Kostas Chloros will install the fiber laser system and align the diagnostic system and launch telescope.

Program Plan. The Gantt chart for the project is shown in Figure 11. The project is organized in its work breakdown structure (WBS) along subsystems/tasks lines. The impact of observing downtime for users of the old AO system is minimized by scheduling its decommissioning and the installation of the new system during the winter months of 2011.

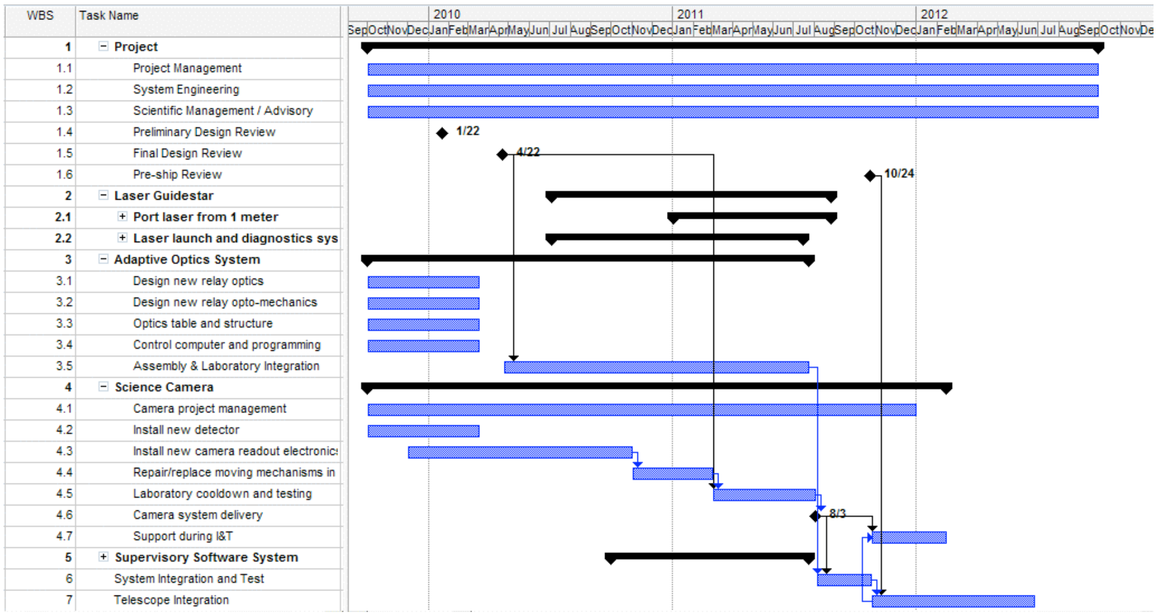


Figure 11. Shane Telescope Adaptive Optics Project Gannt Chart

Important project plan consideration about the laser.

A key assumption about this project plan is that the fiber laser has been previously installed on the Villages AO system at the Nickel telescope in the year prior to its installation at the Shane telescope (2009-10). The present project plan accounts only for the costs of porting the laser from the Nickel to the Shane in 2011, and not the costs of delivery, installation, and mountaintop testing in 2010 at the Nickel. The Villages laser guidestar upgrade was proposed to the Advanced Telescopes and Integration (ATI) program, Astronomy Division, in November 2008 and the proposal is currently in review. The project plan for this MRI proposal is dependent upon funding and execution of the ATI project or an alternative arrangement for an approximately $300k subcontract award to the Lawrence Livermore National Laboratory (LLNL) for setup and checkout of its laser at the observatory. The laser itself was developed with NSF funds provided through the Center for Adaptive Optics and the Adaptive Optics Development Program, and will be donated to UCO/Lick by LLNL. The observatory will be obligated to pursue alternative sources of funding for installation of the laser system should the ATI funds not be available for this purpose.

Risk. Major project risks and their mitigation plans are outlined in the table below:

Risk	Impact on Project	Mitigation Plan
Laser does not perform as expected in terms of anticipated power output or guide star return signal.	Impacts the Laser Guidestar (LGS) mode of operation. May restrict observation to best seeing nights or severely lower the sky coverage and science target sets if LGS mode cannot be used.	Laser will be thoroughly tested in the laboratory prior to installation. Laser will be operated in CW mode which is the highest output power mode for this type of laser and the highest expected marginal return per watt in interaction with the sodium layer. (Denman et. al., 2006)

IR camera requires substantial modifications to accommodate the new detector.	Delays to in the design or integration phase of the project. Increased down-time for AO on the telescope.	The most conservative scenario for camera modification has been accounted for in the cost and effort estimates.
The MEMS deformable mirror fails to operate as expected, or delayed in delivery	The Strehl and sensitivity improvements will not be achieved. A delay in delivery will result in a later than anticipated start date for commissioned instrument science observing at the telescope.	The selected DM is a model that has been thoroughly tested in the Laboratory for Adaptive Optics and is a commercial off-the-shelf item. The vendor contract will be firm fixed price with defined minimum performance requirements and a fixed delivery date. A penalty for late delivery will be considered, with a trade against possible increased cost of such a contract.

Knowledge Transfer. The telescope and commissioning plan includes the effort for updating the AO and IR camera instrument manuals and for training instrument operations staff, who will subsequently assist observers with science observations. The instrument user interface and telescope interface software is a standard system that is presently used on both the 3-meter AO system and on the Villages AO system. This system undergoes continual improvement by the Observatory Software Programming Group in consultation with instrument operators as part of ongoing observatory maintenance. The supervisory software system provides for semi-automated calibration procedures and operations of the AO system with minimal intervention by the operator. LGS mode requires one AO operator and one laser technician.

The new fiber laser system will be installed and commissioned by the same personnel who operate and maintain the current dye laser system, thus providing “on the job” training. The observatory laser technicians will also undergo advanced laser and laser safety training as appropriate, which will be facilitated by the UCO/Lick Observatory in concert with the laser developer, the Lawrence Livermore National Laboratory.

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Roe, H. G., Gavel, D., Max, C., de Pater, I., Gibbard, S., Macintosh, B., & Baines, K. H. Near-Infrared Observations of Neptune's Tropospheric Cloud Layer with the Lick Observatory Adaptive Optics System, AJ 122, 1636 (2001)

<u>Donald T. Gavel</u>, *<u>Director, UCO/Lick Observatory Laboratory for Adaptive Optics</u>*
University of California, Santa Cruz
1156 High Street, Santa Cruz, CA 95064
831-459-5464 • gavel@ucolick.gov

(a) Professional Preparation

Massachusetts Institute of Technology	Electrical Engineering	B.S., 1975
Stanford University	Electrical Engineering	M.S., 1976
University of California, Davis	Electrical Engineering	Ph.D., 1988

(b) Appointments

Director, UCO/Lick Observatory Laboratory for Adaptive Optics, 2003-present.

Project Scientist, Lawrence Livermore National Laboratory (LLNL) Astronomical Adaptive Optics Program, 1998-2003.

Principal Investigator: Visible Light Laser Guidestar Experiments, NSF Small Grant for Exploratory Research (#0649261), 2006-2008.

Co-Investigator (with Prof. Claire Max): Active Galactic Nuclei, LLNL IR&D project, Exploratory Research In the Institutes, Institute for Geophysics and Planetary Physics, FY 1999-2002.

Project Scientist, Ophthalmic Imaging Instruments for the Eye, DOE Biomedical Engineering Grant, FY 2002-2003.

Principal Investigator: Solar System Events at High Spatial Resolution, LLNL IR&D project, Exploratory Research In the Institutes, Institute for Geophysics and Planetary Physics, FY 1996-1997.

Co-Investigator: Laser Guided Adaptive Optics for Astronomy, LLNL Director's Initiative Project, FY 1993-1997.

(c-i) Five Selected Publications

1. Gavel, D., *Laser Technology for Astronomical Adaptive Optics*, (Invited paper), **Proceedings of the SPIE**, Vol., 7015, June 2008.

2. Thomas, S. J., Adkins, S., Gavel, D., Fusco, T., Michau, V., *Study of optimal wavefront sensing with elongated laser guide stars*, **Monthly Notices of the Royal Astronomical Society**, Volume 387, Issue 1, pp. June 2008, 173-187.

3. Gavel, D.T., *A Comparison of Tomography Reconstruction Techniques for Multi-conjugate and Multi-object Adaptive Optics: Theory and Laboratory Experience*, **OSA Topical Meeting on Adaptive Optics**, Victoria, Canada, June 2007.

4. Wiberg, D.M., Max, C.E., and Gavel, D.T., *Geometric view of adaptive optics control*, **Journal Of The Optical Society Of America A**, 22, 5, pp 870-880, May 2005.

5. Poyneer, L.A., Gavel, D.T., and Brase, J.M., *Fast wavefront reconstruction in large adaptive optics systems using the Fourier transform*, **Journal Of The Optical Society Of America A**, V 19, n 10, November 2002, 2100-2111.

(c-ii) Five Additional Publications

1. Gavel, D.T., *A Comparison of Tomography Reconstruction Techniques for Multi-conjugate and Multi-object Adaptive Optics: Theory and Laboratory Experience*, **OSA Topical Meeting on Adaptive Optics**, Victoria, Canada, June 2007.

2. Gavel, D.T., *Microelectro-mechanical systems (MEMS) Development for Astronomical Instrumentation at the Lick Observatory Laboratory for Adaptive Optics*, **Proceedings of the SPIE**, Vol. 6467, January 2007, 646702.

3. Gavel, D.T., Reinig, M., Cabrera, C., *Fast Hardware Implementation of Tomography for Multi-guidestar Adaptive Optics*, **Proceedings of the SPIE**, Vol. 5903, San Diego, August 2005.

4. Gavel, D.T., *Stability of Closed Loop Tomography Algorithms for Adaptive Optics*, **OSA Topical Meeting on Adaptive Optics Analysis and Methods**, Charlotte, NC, June 2005.

5. Gavel, D.T., *Tomography for multiconjugate adaptive optics systems using laser guide stars*, **Proceedings of the SPIE,** Vol. 5490, Glasgow, Scotland, June 2004.

(d) Five Synergistic Activities

- Member, Executive Committee for Keck Observatory Next Generation Adaptive Optics
- Organizer, CfAO Workshops on Laser Technology and Systems for Astronomy (2006-8)
- Organizing Committee, SPIE Telescopes and Instrumentation Conference on Adaptive Optics (2006, 2008)
- Organizing Committee, OSA Topical Meeting on Adaptive Optics (2005, 2007)
- Chairman, Thirty Meter Telescope Adaptive Optics Working Group (2003-4)

(e) Collaborators & Other Affiliations

<u>Collaborators</u>
Mike Bolte, UCSC
Michael Helmbrech, IRISAO
Joel Kubby, UCSC
Scot Olivier, LLNL
Scott Severson, UCSC
Dragoslav Siljak, University of Santa Clara
Wallace Tang, MicroAssembly Tech.
Jack Werner, UC Davis
Stan Woosley, UCSC

<u>Graduate Students Advised (5 total during last 5 years)</u>
Mark Ammons, UCSC; Jess Johnson, UCSC; Katie Morzinski, UCSC; (coadvisor) Bautista Fernandez, UCSC; Eddie Laag, UC Riverside

<u>Postdoctoral Fellows Sponsored (2 total during last 5 years)</u>
Renate Kupke, UCSC; Sandrine Thomas, UCSC

Selected Honors and Awards

- 2003 R&D 100 Award, MEMS-Based Adaptive Optics Phoropter, (U.S. Patent #7,195,354, 3/2007).
- LLNL Physics and Technology Directorate Award, 2003 (for MEMS Phoropter work)
- LLNL Physics and Technology Directorate Award, 2002 (for work on the Lick Laser Guidestar Adaptive Optics system)
- LLNL Physics and Technology Directorate Award, 2000 (best paper, Titan: High-Resolution Speckle Images from the Keck Telescope)

Claire E. Max (co-PI)

(a) Professional Preparation

Undergraduate Institution

Harvard University	Major: Astronomy	A.B. magna cum laude	1968

Graduate Institution

Princeton University	Major: Astrophysical Sciences	PhD	1972

Post-Doctoral Fellowship Institution

University of California, Berkeley	Physics Department	1972-1974

(b) Appointments

2008–	Director, University of California Center for Adaptive Optics
2004–	Director, National Science Foundation Center for Adaptive Optics
2001–	Astronomer, University of California Observatories/Lick Observatory and Professor, Department of Astronomy and Astrophysics, University of California at Santa Cruz
1995–2000	Director of University Relations, Lawrence Livermore National Laboratory
1993–1995	Director of Institutes, Physical Sciences Directorate, Lawrence Livermore Nat'l Laboratory
1984–1993	Founding Director, Livermore Branch, Inst. Geophysics & Planetary Physics, Univ. Calif.
1974–2004	Physicist, Lawrence Livermore National Laboratory, University of California

(c) Honors and Awards

2009	Madison Medal, Princeton University
2008	National Academy of Sciences
2004	E. O. Lawrence Award (Department of Energy)
2002	American Academy of Arts and Sciences

(d) Publications

Publications related to the project

1. "Design, layout, and early results of a feasibility experiment for sodium-layer laser-guide-star adaptive optics," C.E. Max, K. Avicola, J.M. Brase, H.W. Friedman, H.D. Bissinger, J. Duff, D.T. Gavel, J.A. Horton, R. Kiefer, J.R. Morris, S.S. Olivier, R.W. Presta, D.A. Rapp, J.T. Salmon and K.E. Waltjen. *Optical Society of America Journal A*, **11**, 813-824, 1994.
2. "Image Improvement from a Sodium-Layer Laser Guide Star Adaptive Optics System," C.E. Max, S.S. Olivier, H.W. Friedman, J. An, K. Avicola, B.V. Beeman, H.D. Bissinger, J.M. Brase, G.V. Erbert, D.T. Gavel, K. Kanz, M.C. Liu, B. Macintosh, K.P. Neeb, J. Patience and K.E. Waltjen. *Science*, **277**, 1649–1652, 1997.
3. "Merging Galaxies in GOODS-S: First Extragalactic Results from Keck Laser Adaptive Optics," J. Melbourne, S.A. Wright, M. Barczys, A.H. Bouchez, J. Chin, M.A. van Dam, S. Hartman, E. Johansson, D.C. Koo, R. Lafon, J. Larkin, D. Le Mignant, J. Lotz, C.E. Max, D.M. Pennington, P.J. Stomski, D. Summers and P.L. Wizinowich. ApJ Letters, 625, L27-L30, 2005.
4. "Locating the Two Black Holes in NGC 6240," C. E. Max, G. Canalizo, & W. H. de Vries, 2007, *Science*, 316, 1877.
5. "Spatially Resolved Stellar Populations of Eight GOODS-South AGN at z~1," S. Mark Ammons, Jason Melbourne, Claire E. Max, David C. Koo, David J. V. Rosario, 2008, *AJ*, 137, 470.

Other publications

1. "Cloud Structures on Neptune Observed with Keck Telescope Adaptive Optics," C. E. Max, B. A. Macintosh, S. G. Gibbard, D. T. Gavel, H. G. Roe, I. de Pater, A.M. Ghez, D. S. Acton, O. Lai, P. Stomski and P. L. Wizinowich. AJ, 125, 364-375, 2003.
2. "Adaptive Optics Imaging and Spectroscopy of Cygnus A. I. Evidence for a Minor Merger," G. Canalizo, C. Max, D. Whysong, R. Antonucci and S.E. Dahm. ApJ, 597, 823-831, 2003.

3. “Super-resolving distant galaxies with gravitational telescopes: Keck-LGSAO and Hubble imaging of the lens system SDSSJ0737+3216,” Marshall, P. J.; Treu, T.; Melbourne, J.; Gavazzi, R.; Bundy, K.; Ammons, S. M.; Bolton, A. S.; Burles, S.; Larkin, J. E.; Le Mignant, D.; Koo, D. C.; Koopmans, L. V. E.; Max, C. E.; Moustakas, L. A.; Steinbring, E.; & Wright, S. A., ApJ, 671, 1196, 2007.
4. “Rest-Frame R-band Light Curve of a z ~ 1.3 Supernova Obtained with Keck Laser Adaptive Optics,” Melbourne, J.; Dawson, K. S.; Koo, D. C.; Max, C.; Larkin, J. E.; Wright, S. A.; Steinbring, E.; Barczys, M.; Aldering, G.; Barbary, K.; Doi, M.; Fadeyev, V.; Goldhaber, G.; Hattori, T.; Ihara, Y.; Kashikawa, N.; Konishi, K.; Kowalski, M.; Kuznetsova, N.; Lidman, C.; Morokuma, T.; Perlmutter, S.; Rubin, D.; Schlegel, D. J.; Spadafora, A. L.; Takanashi, N.; & Yasuda, N., AJ, 133, 2709, 2007.
5. “The W. M. Keck Observatory Laser Guide Star Adaptive Optics System: Overview,” Wizinowich, Peter L.; Le Mignant, David; Bouchez, Antonin H.; Campbell, Randy D.; Chin, Jason C. Y.; Contos, Adam R.; van Dam, Marcos A.; Hartman, Scott K.; Johansson, Erik M.; Lafon, Robert E.; Lewis, Hilton; Stomski, Paul J.; Summers, Douglas M.; Brown, Curtis G.; Danforth, Pamela M.; Max, Claire E.; & Pennington, Deanna M., PASP, 118, 297-309, 2006.

(e) Synergistic Activities

1. Director, NSF Center for Adaptive Optics and Univ. of Calif. Center for Adaptive Optics
2. Other leadership positions: Project Scientist, Keck Observatory Next Generation Adaptive Optics
3. Originator and project leader for the Akamai Short Course and Internship on the Big Island of Hawaii. This is a Center for Adaptive Optics program aimed at increasing the participation of Hawaiian community college-age students in the scientific and technical workforce. Optics and observatory operations are at the core of this summer internship experience.
4. Co-founder of the Institute for Scientist and Engineer Educators at UC Santa Cruz. This program is a spin-off from the Center for Adaptive Optics, with the goal of introducing science and engineering graduate students on our campus to modern knowledge and practice of teaching and learning, and then using these new skills in outreach programs to students from groups that are under-represented in science and engineering.
5. Member, Astro 2010 Committee, National Research Council, National Academy of Sciences

(a) Collaborators & Other Affiliations

List of all collaborators and co-editors within the last 48 months

Ammons, S. M. (UCSC), Antonucci, R. (UCSB), Barczys, M. (no current affiliation), Bouchez, A.H. (Caltech), Brown, M.E. (Caltech), Brown, C.G. (LLNL), Campbell, R.D. (Keck), Canalizo, G. (UC Riverside), Chin, J. (Keck), Chun, M.R. (U. Hawaii), Danforth, P.M. (LLNL), de Pater, I. (UC Berkeley), de Vries, W.H. (UC Davis), Gates, E.L. (Lick Obs.), Gavel, D. (UCSC), Ghez, A.M. (UCLA), Gibbard, S.G. (LLNL), Graham, J.R. (UC Berkeley), Johansson, E.M. (Keck), Kalas, P. (UC Berkeley), Koo, D.C. (UCSC), Larkin, J. (UCLA), Le Mignant, D. (Keck), Lewis, H. (Keck), Lloyd, J.P. (Cornell), Macintosh, B.A. (LLNL), Marshall, P. J. (UCSB), McKay, C.P. (NASA Ames), Melbourne, J. (Caltech), Metevier, A. (Sonoma State), Pennington, D.M. (LLNL), Perlmutter, S. (UC Berkeley), Perrin, M.D. (UCLA), Pollack, L.K. (Apple), Raschke, L. (UCSC), Roe, H.G. (Lowell Obs.), Rosario, David J. V. (UCSC), Schlegel, D. J. (LBNL), Schneider, G. (U Ariz.), Simard, L. (HIA), Steinbring, E. (HIA), Stomski, P.J. (Keck), Summers, D. (Keck), Treu, T. (UCSB), van Dam, M.A. (in New Zealand), Whysong, D. (NRAO), Wiberg, D.M. (UCSC), Wizinowich, P.L. (Keck), Wright, S.A. (UC Irvine)

Graduate Advisors: Francis Perkins (retired, formerly of Princeton University).

Postdoctoral Sponsor: Alan Kaufman (retired, formerly of University of California, Berkeley).

Graduate Students (3): Lynne Raschke (UC Santa Cruz), Jason Melbourne (California Inst. of Technology), S. Mark Ammons (finishing PhD in June 09).

Postgraduate-Scholar Sponsor in past 5 years: Elizabeth McGrath (UC Santa Cruz).

Biographical Sketch: Constance M. Rockosi

Professional Preparation

Princeton University, B.S.E. Electrical Engineering, Certificate in Engineering Physics, 1993

University of Chicago, M. Sc. Astronomy and Astrophysics 1994

University of Chicago, Ph. D. Astronomy and Astrophysics 2001

Appointments

9/2004 - Present Assistant Astronomer/Assistant Professor, UCO/Lick Observatory and Astronomy Department, University of California Santa Cruz

10/2001 - 9/2004 Hubble Postdoctoral Fellow, University of Washington, Seattle

9/1996 - 9/2001 Research Assistant

9/1993 - 9/1995 NSF Graduate Student Research Fellowship

Relevant Publications

Allende Prieto, C., Sivarani, T., Beers, T. C., Lee, Y. S., Koesterke, L., Shetrone, M., Sneden, C., Lambert, D. L., Wilhelm, R., Rockosi, C. M., Lai, D., Yanny, B., Ivans, I. I., Johnson, J. A., Aoki, W., Bailer-Jones, C. A. L., & Re Fiorentin, P. 2007, "The SEGUE Stellar Parameter Pipeline. III. Comparison with High-Resolution Spectroscopy of SDSS/SEGUE Field Stars," ArXiv e-prints, 710, arXiv:0710.5780

Lee, Y. S., Beers, T. C., Sivarani, T., Johnson, J. A., An, D., Wilhelm, R., Allende Prieto, C., Koesterke, L., Re Fiorentin, P., Bailer-Jones, C. A. L., Norris, J. E., Yanny, B., Rockosi, C. M., Newberg, H. J., Cudworth, K. M., & Pan, K. 2007, "The SEGUE Stellar Parameter Pipeline. II. Validation with Galactic Globular and Open Clusters," ArXiv e-prints, 710, arXiv:0710.5778

Lee, Y. S., Beers, T. C., Sivarani, T., Allende Prieto, C., Koesterke, L., Wilhelm, R., Norris, J. E., Bailer-Jones, C. A. L., Re Fiorentin, P., Rockosi, C. M., Yanny, B., Newberg, H., & Covey, K. R. 2007, "The SEGUE Stellar Parameter Pipeline. I. Description and Initial Validation Tests," ArXiv e-prints, 710, arXiv:0710.5645

Newberg, H. J., Yanny, B., Rockosi, C. M., Grebel, E. K., Rix, H.-W., et al., 2002, "The Ghost of Sagittarius and Lumps in the Halo of the Milky Way," ApJ, 569, 245.

Rockosi, C. M., Odenkirchen, M., Grebel, E. K., Dehnen, W., Cudworth, K. M., Gunn, J. E., & York, D. G., 2002, "A Matched-Filter Analysis of the Tidal Tails of the Globular Cluster Palomar 5," AJ, 124, 349.

Other Publications

Belokurov, V., Evans, N. W., Bell, E. F., Irwin, M. J., Hewett, P. C., Koposov, S., Rockosi, C. M., Gilmore, G., Zucker, D. B., Fellhauer, M., Wilkinson, M. I., Bramich, D. M., Vidrih, S., Rix, H.-W., Beers, T. C., Schneider, D. P., Barentine, J. C., Brewington, H., Brinkmann, J., Harvanek, M., Krzesinski, J., Long, D., Pan, K., Snedden, S. A., Malanushenko, O., & Malanushenko, V. 2007, "The Hercules-Aquila Cloud," ApJL, 657, L89

Zucker, D. B., Kniazev, A. Y., Martínez-Delgado, D., Bell, E. F., Rix, H.-W., Grebel, E. K., Holtzman, J. A., Walterbos, R. A. M., Rockosi, C. M., York, D. G., Barentine, J. C., Brewington, H., Brinkmann, J., Harvanek, M., Kleinman, S. J., Krzesinski, J., Long, D., Neilsen, E. H., Jr., Nitta, A., & Snedden, S. A. 2007, "Andromeda X, a New Dwarf Spheroidal Satellite of M31: Photometry," ApJL, 659, L21

Belokurov, V., et al. 2007, "Cats and Dogs, Hair and a Hero: A Quintet of New Milky Way Companions," ApJ, 654, 897

Helmi, A., Ivezić, Ž., Prada, F., Pentericci, L., Rockosi, C. M., Schneider, D. P., Grebel, E. K., Lupton, R. H., Gunn, J. E., Knapp, G. R., Strauss, M. A., & Brinkmann, J., 2003, "Selection of Metal-poor Giant Stars Using the Sloan Digital Sky Survey Photometric System," ApJ, 586, 195.

Synergistic Activities

2006 Stanford Linear Accelerate Center Director's Review Committee for the Large Synoptic Survey Telescope

2006 NSF Major Research Instrumentation review panel

2005 Co-chair of National Optical Astronomical Observatory review panel for a Blanco major instrumentation proposal

2005 NASA review panel for UV/Optical detector development proposals

Collaborators and Co-Editors

Carlos Allende Prieto, University of Texas; Timothy C. Beers, Michigan State University; Julianne Dalcanton, University of Washington, Seattle; Heather Morrison, Case Western Reserve University; Heidi Newberg, Rensselaer Polytechnic University; Ronald Wilhelm, Texas Tech; Beth Willman, New York University; Brian Yanny, Fermilab

Coauthors on SDSS papers can be found listed in the SDSS Fifth Data Release paper, Adelman-McCarthy et al., 2006, ApJS, 172, 634

Graduate and Postdoctoral Advisors: Donald G. York, University of Chicago; Julianne Dalcanton, University of Washington, Seattle

Thesis Advisees and Postgraduate-Scholars Sponsored: No declared advisees advanced to PhD candidacy at this time.