Deployment of low-cost replicable laser adaptive optics on 1-3 meter class telescopes

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Adaptive optics (AO) is now a productive, routine science capability on the nation's largest apertures, producing over 100 refereed science publications per year. While the greatest resolution and sensitivity gains have been realized with these AO systems, many science programs such as large astronomical surveys, synoptic monitoring, rapid transient characterization, and programs requiring high-angular resolution in the visible, have not yet enjoyed the benefits of national investment in astronomical AO capabilities. Our group is deploying a low-cost, autonomous, integrated laser adaptive optics system and science instrument called CAMERA on the fully robotic 1.5 m telescope at Palomar Observatory. When deployed on sky, CAMERA will serve as an archetype for a new class of affordable AO system deployable on most 1-3 meter telescopes, bringing the benefit of routine high-angular-resolution science to the wide community of moderate-diameter US telescopes.

1. Introduction

Adaptive optics (AO) is now a productive, routine science capability on the nation's largest apertures, producing over 100 refereed science publications per year [1]. AO publications rates at Keck and Gemini, in particular, have rapidly accelerated with the deployment of their respective laser guide star (LGS) AO systems. While the greatest resolution and sensitivity gains have been realized on these largest apertures, their complexity limits their observing efficiency, component technology limits their operation to near-infrared wavelengths, and high oversubscription of these apertures limits community access. As a result, large survey programs, synoptic monitoring, rapid transient characterization, and programs requiring diffraction-limited visible light have not yet enjoyed the benefits of national investment in AO capabilities.

Our group is in the process of deploying a low-cost, autonomous, Rayleigh LGS AO system and science instrument nicknamed CAMERA (Compact Affordable MEMS-based Rayleigh Adaptive optics) on the fully robotic 1.5 m telescope at Palomar Observatory. By providing high-angular-resolution and high-sensitivity visible and near-infrared science with unprecedented observing efficiency, CAMERA will enable exploration of science parameter spaces inaccessible to large diameter telescope AO systems. Based on a successful closed-loop laboratory AO system prototype, CAMERA will mitigate risk and cost via reuse of proven, well-understood components and rigorously modularized and regression-tested system control software. When deployed on sky, CAMERA will serve as an archetype for a new class of affordable AO system deployable on 1-3 meter telescopes, bringing the benefit of adaptive optics to the wide community of moderate-diameter US telescopes.

The continued importance of mid-sized telescopes for broad United States astronomy was recently highlighted in the 2008 United States Adaptive Optics Roadmap [2]. Recognizing the limitations of large apertures, the Roadmap noted among its recommendations that,

> *"Mid-sized telescopes provide compelling opportunities for world-class science in specialized fields not typically accessible on larger telescopes due to limitations imposed by schedule / observing model and in some cases specialized capabilities."*

Our team has responded to this recommendation by identifying three broad categories of science where CAMERA will provide a unique new capability:

> Large surveys. Covering several thousand targets each, these high-angular-resolution imaging surveys would be extremely time-intensive on currently available LGS AO systems. CAMERA's low overhead time and queued, robotic operation enable very efficient operation for entirely new AO surveys.
>
> Rapid transient characterization. CAMERA will provide high-angular-resolution images of transient events within a few minutes of their detection. Targets generated by existing and future survey projects[1] can be rapidly observed by CAMERA, providing significant sensitivity improvements over seeing-limited observations.
>
> Time-domain astronomy. CAMERA's robotic queued operation supports recurrent, regularly spaced observations of specific targets. This will enable synoptic monitoring programs that are difficult to pursue on existing AO systems.

Thus we have developed the CAMERA design to emphasize time-domain astronomy where high-cadence, high-availability observations are of comparable or greater importance to achieving new astronomical understanding than aperture collecting area alone.

The 2008 AO Roadmap also highlighted the unique role of moderate diameter telescopes in our national infrastructure by noting,

> *"Mid-sized telescopes remain compelling platforms for AO development and risk mitigation, accelerating the realization of new science capabilities on larger telescopes."*

To this end, CAMERA will also serve as a pathfinder for lower-cost technologies in AO system development, including the use of micro-electromechanical systems (MEMS) deformable mirrors, and industrial guide star lasers. The computer architecture will be robust, relying on a single, simple PC, and operations will be fully automated, further reducing lifecycle costs. The aggressive open-shutter efficiency of CAMERA will set a standard for future large-telescope LGS AO systems to emulate. Finally, the Roadmap emphasized the role of mid-sized telescopes in student training to maintain a pipeline of experts to lead subsequent generations of AO system on our largest apertures. CAMERA not only includes direct student involvement, but offers a paradigm with the potential for widespread student involvement, by offering an affordable AO architecture to dozens of mid-sized observatories.

CAMERA represents an initial step toward disseminating a cost-effective replicable adaptive optics design platform which can transform the role of mid-sized telescopes in the United States and around the world. After proving the concept and verifying performance, we will release detailed CAMERA technical designs in the published literature and release CAMERA control software widely under public license. This will facilitate the technical development needed throughout the community to deploy similar AO systems, ultimately increasing scientific throughput of a substantial fraction of our nation's mid-sized aperture telescopes.

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[1] e.g. Catalina Sky Survey, Robotic Transient Search Experiment, Palomar Transient Factory (PTF), Pan-STARRS and, later, LSST.

2. The CAMERA laser adaptive optics system

The CAMERA laser adaptive optics system is designed around the philosophy of using only field tested and proven off-the-shelf components to mitigate development and replication costs. The system comprises a Rayleigh laser guide star, a Cassegrain mounted adaptive optics system with integrated science cameras, and a PC-based real-time reconstructor and control computer. The laser guide star uses an industrial turn-key laser system with a projector mounted within the secondary hub. The Cassegrain instrument (see Figure 1) includes a cost effective micro-electromechanical deformable mirror and commercially available detectors for visible and infrared science imaging and wavefront sensing. The fore-optics are additionally interchangeable to easily adapt to differing F/#s making the CAMERA system portable to a wide range of different telescope designs. The real-time and control architecture for CAMERA will be based around a single PC running Linux/C++. CAMERA will be fully automated, making it easy to use and operate with an emphasis on high observing efficiency.

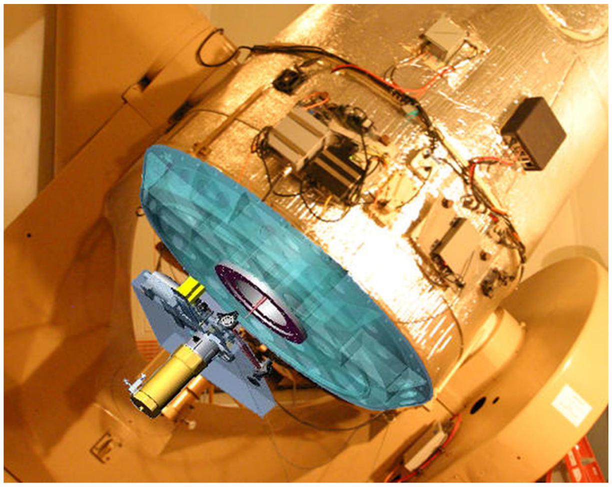


Figure 1. An opto-mechanical model of the CAMERA adaptive optics and science instrument system interfaced to the Palomar 1.5 m telescope.

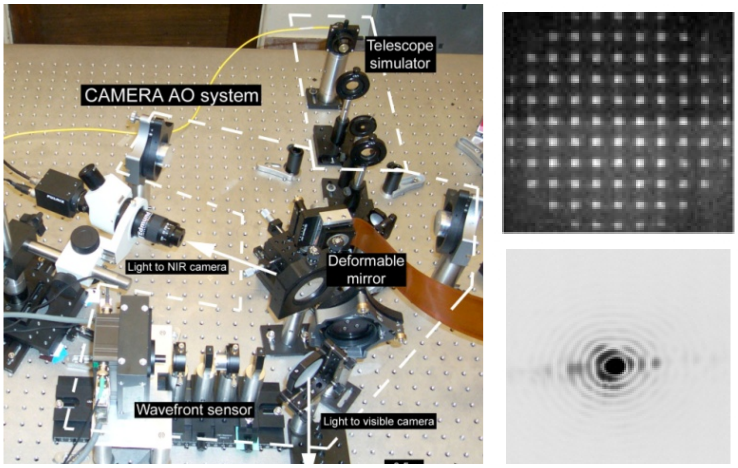


Figure 2 Closed-loop laboratory version of CAMERA (left) and the closed-loop wavefront sensor and science camera image planes during correction of dynamic optical aberrations (right).

A laboratory version of the CAMERA AO system has been demonstrated to correct dynamic optical aberrations in closed-loop [3]. Figure 2 shows an annotated picture of the laboratory system. The system operated at >100Hz with a reduction in the RMS residual phase error by a factor of ten.

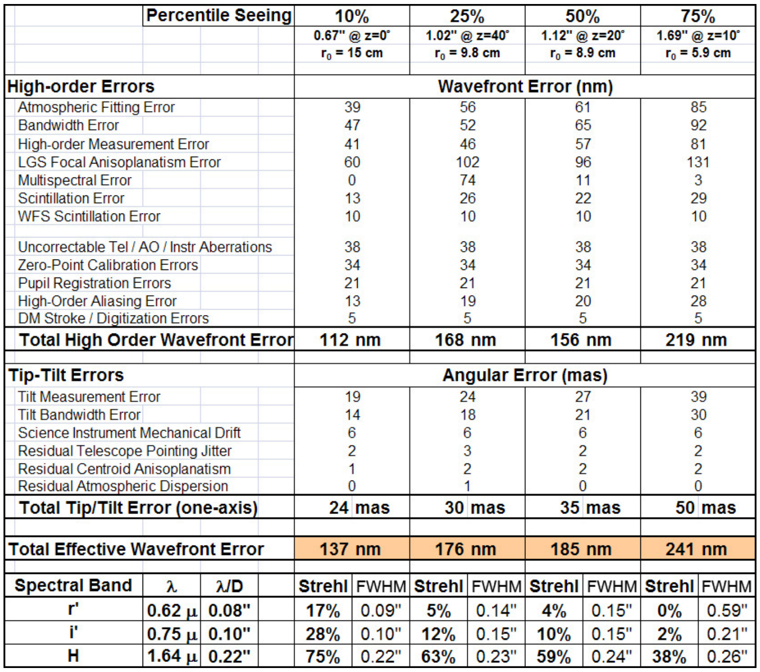
We have developed detailed error budgets for CAMERA's expected adaptive optics performance (see Table 1) under different observing conditions at Mt. Palomar where seeing conditions are modest (median seeing ~ 1.1" in the visible). Utilizing measured C_n^2(h) profiles from a local MASS-DIMM atmospheric turbulence monitor collected over a year's baseline, we expect dramatic image improvement in all conditions at infrared wavelengths and access to visible near-diffraction-limited imagery under median conditions, assuming we adopt the manageable constraint of operating the system closer to zenith during periods of poor seeing. During 25th best percentile seeing, CAMERA will achieve appreciable Strehl ratios in the visible red wavelengths over ~1.5 steradians. As seeing conditions degrade, the amount of available sky where visible correction can be achieved decreases. However, even under poor conditions (75th percentile), reasonable correction in the near-infrared can still be achieved within 10° of zenith.

With regards to the impact of this operating constraint on CAMERA science (discussed in §3), only the search for companions to nearby stars, where high-contrast is absolutely necessary, requires 10th percentile or better seeing conditions. Long-term transient monitoring and rapid transient characterization, along with asteroid binarity searches require median or better seeing conditions. Other large surveys for nearby stellar companions and lensed quasars, and monitoring of solar system objects can be executed even in times of poor (75th percentile) seeing, albeit with a more restricted zenith pointing. With a robust queue-scheduled portfolio of science programs, CAMERA will remain scientifically effective in nearly all environmental conditions in which the observatory would allow observations.

These error budgets are based on our team's considerable real-world experience building and commissioning AO systems at Palomar and MMT, and in measuring the performance of the Keck AO system. At Palomar, we find delivered LGS Strehl performance is usually within 10% (relative) of our detailed model predictions, giving us strong confidence in our performance predictions for CAMERA.

In addition to the fundamental atmospheric terms for residual high-order and tip-tilt wavefront error, we have allowed for conservative implementation errors based again on our practical experience. For example, uncorrectable high-spatial-frequency aberrations are conservatively estimated by extrapolating measured values from the Palomar 5m telescope AO system. Errors arising from pupil misregistration have similarly been allocated from experience and can be achieved with high confidence.

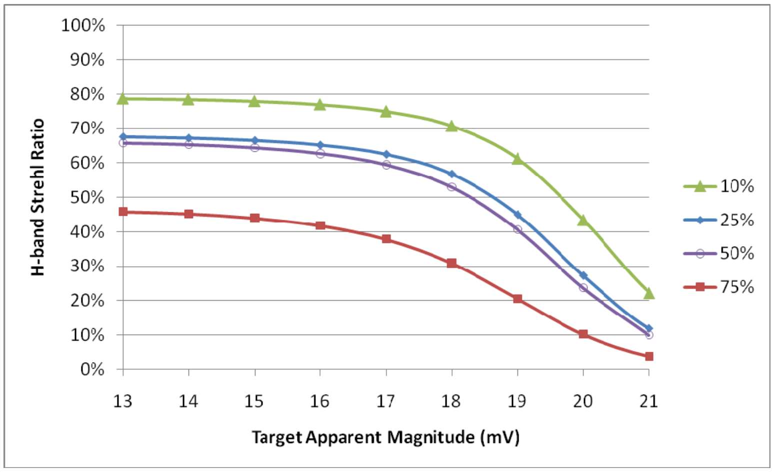
Figure 3 shows CAMERA's estimated H-band Strehl ratio as a function of science target magnitude and observing conditions. For bright guide sources, $m_V < 15$, performance is limited by the seeing conditions and the high-order wavefront error. Beyond $m_V = 17$, tip-tilt errors start to dominate, affecting the overall AO correction. However even in median seeing conditions, Strehl ratios of > 40% will be achieved in H-band using an on-axis $m_V = 19$ science target.



Percentile Seeing			10%		25%		50%		75%	
			0.67" @ z=0° r_0 = 15 cm		1.02" @ z=40° r_0 = 9.8 cm		1.12" @ z=20° r_0 = 8.9 cm		1.69" @ z=10° r_0 = 5.9 cm	
High-order Errors			**Wavefront Error (nm)**							
Atmospheric Fitting Error			39		56		61		85	
Bandwidth Error			47		52		65		92	
High-order Measurement Error			41		46		57		81	
LGS Focal Anisoplanatism Error			60		102		96		131	
Multispectral Error			0		74		11		3	
Scintillation Error			13		26		22		29	
WFS Scintillation Error			10		10		10		10	
Uncorrectable Tel / AO / Instr Aberrations			38		38		38		38	
Zero-Point Calibration Errors			34		34		34		34	
Pupil Registration Errors			21		21		21		21	
High-Order Aliasing Error			13		19		20		28	
DM Stroke / Digitization Errors			5		5		5		5	
Total High Order Wavefront Error			**112 nm**		**168 nm**		**156 nm**		**219 nm**	
Tip-Tilt Errors			**Angular Error (mas)**							
Tilt Measurement Error			19		24		27		39	
Tilt Bandwidth Error			14		18		21		30	
Science Instrument Mechanical Drift			6		6		6		6	
Residual Telescope Pointing Jitter			2		3		2		2	
Residual Centroid Anisoplanatism			1		2		2		2	
Residual Atmospheric Dispersion			0		1		0		0	
Total Tip/Tilt Error (one-axis)			**24 mas**		**30 mas**		**35 mas**		**50 mas**	
Total Effective Wavefront Error			**137 nm**		**176 nm**		**185 nm**		**241 nm**	
Spectral Band	**λ**	**λ/D**	**Strehl**	FWHM	**Strehl**	FWHM	**Strehl**	FWHM	**Strehl**	FWHM
r'	**0.62 μ**	**0.08"**	**17%**	0.09"	**5%**	0.14"	**4%**	0.15"	**0%**	0.59"
i'	**0.75 μ**	**0.10"**	**28%**	0.10"	**12%**	0.15"	**10%**	0.15"	**2%**	0.21"
H	**1.64 μ**	**0.22"**	**75%**	0.22"	**63%**	0.23"	**59%**	0.24"	**38%**	0.26"

Table 1 Example error budget for CAMERA under different seeing conditions (r_0) and for different zenith angles (z) assuming an on-axis m_V=17 star for tip-tilt sensing and on-axis science target. Measurement error arises from finite photoreturn, WFS read noise, sky noise, dark current, and other factors. Focal anisoplanatism is an error arising from the finite altitude of the Rayleigh LGS resulting in imperfect atmospheric sampling. Multispectral error arises from differential refraction of UV and H-band optical rays and grows rapidly for large off-zenith angles. For extended targets an additional 65 nm RMS of angular anisoplanatism error would be present at a field position 10 arcseconds removed from the direction of the LGS (finite aperture effects on the 1.5 m telescope mitigate the classical calculation of isoplanatic angle.) 'mas' indicates milliarcseconds, " indicates arcseconds.

Figure 3. Calculated H-band Strehl ratios for CAMERA under the various observing conditions presented in Table 1 for different visual magnitudes of on-axis tip-tilt star. Because of CAMERA's precision correction of high-order wavefront errors, the tip-tilt star is subject to significant sharpening, dramatically improving the tip-tilt measurement performance and enabling use of uncharacteristically faint tip-tilt guide stars.



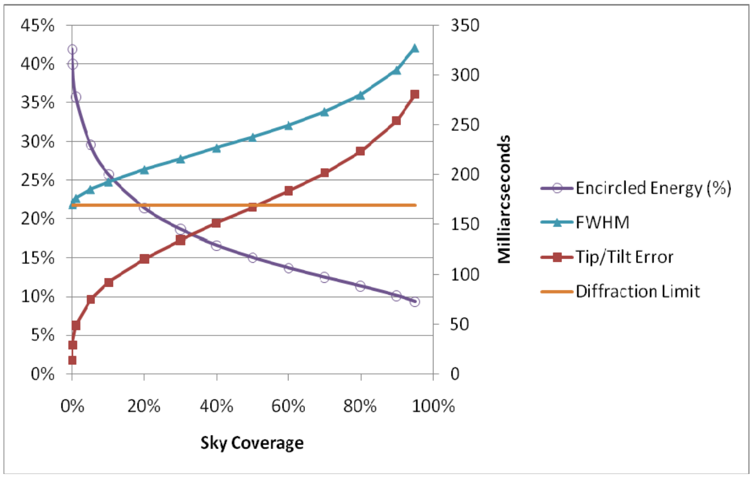


Figure 4. H-band imaging and energy concentration metrics for CAMERA as a function of sky coverage for observations where the tip-tilt star is selected as an off-axis field star, assuming galactic latitude of 30° (at which the average field star density per magnitude approximately equals the celestial average.) As required sky coverage increasing, residual tip-tilt errors grow, blurring but not ruining the imaging resolution. Encircled energy (EE) refers to the left-hand vertical axis and is quoted for a 3-pixel diameter across a Nyquist sampled infrared detector. EE of 18% (corresponding to a Strehl ratio of 25%) is obtained over 30% sky fraction for the 50% seeing condition assumed here.

We have calculated the full-width at half-maximum (FWHM) and encircled energy in the H-band (Figure 4) for cases where the primary science case requires increased signal-to-noise as opposed to high-resolution imaging, such as with long term transient monitoring. When the science target is the tip-tilt source (up to $m_V = 18$), the encircled energy within 3 Nyquist samples is ~30%. Using field tip-tilt stars, at a 20% sky coverage fraction, the percentage of encircled energy has only dropped to 22%. Even over the majority of the sky, the encircled energy will still be greater than 15%.

3. Research Activities

The detailed science cases presented in the following section illustrate some of the broad range of CAMERA's potential contributions to astronomy. CAMERA offers two distinct LGS observation modes[2], targeting different areas of wavelength / sky coverage parameter space and distinguished by use of either an on-axis science target or a nearby field star for tip-tilt wavefront

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[2] Although CAMERA will also support high-order wavefront sensing using a natural guide star (NGS) brighter than approximately $m_V = 10$, its excellent LGS performance and high operational efficiency is expected to make NGS observations relatively rare (though invaluable for commissioning and routine diagnostics.)

measurement. When estimating tip-tilt from the science target itself, we estimate CAMERA can achieve diffraction-limited visible-light performance for point sources as faint as $m_V = 17$ in median conditions (section 3.2 presents detailed performance calculations). Using an off-axis field star for tip-tilt, approximately 30% sky coverage can be accessed with < 230 milliarcsecond H-band resolution, while 90% sky coverage can be accessed with < 300 milliarcsecond FWHM in median seeing. For any specific science case, sequential observing plans can be optimized to use either or both tip-tilt observing mode.

For all described science cases, CAMERA's good sky coverage for diffraction-limited observations and excellent sky coverage for dramatic seeing improvement are sufficient to successfully produce statistically-useful target samples. Each mode offers greatly improved sensitivity and angular resolution; on a 1.5m telescope in median Palomar conditions CAMERA provides comparable H-band SNR to a 4m-class seeing-limited telescope (Table 2).

Band	Palomar Sky Background	Ratio of CAMERA to 1.5m seeing-limited integration time	Ratio of CAMERA to 4m seeing-limited integration time
J	16.4	0.35	2.51
H	15.0	0.14	1.02

Table 2. CAMERA's infrared integration time compared to a seeing-limited system. The calculations assume median seeing, an on-axis $m_V = 16$ tip-tilt star, and observations at the zenith.

3.1. Large surveys

3.1.1. Stellar and substellar companions to all types of stars

CAMERA can perform the largest-ever imaging survey for close companions to nearby stars. We would observe a sample of 10,000 stars within 50 parsecs selected from current databases and new proper motion surveys such as the LSPM survey. This survey will require 4 months of telescope time, allowing the first detailed characterization of the companion population in a single sample with well understood completeness and selection-bias spanning essentially the entire nearby stellar mass range. 120 second exposure times in I & H-bands are sufficient to detect and start to characterize high-mass brown-dwarf companions at > 2 arcsec from the target stars. The sensitivity to closer companions will depend on the brightness of the target stars; brown dwarfs will be detectable down to at least 5 AU separations around nearby M-dwarfs. In addition, CAMERA's visible-light AO capabilities will allow the first large-target-sample high-angular-resolution survey for white dwarf companions.

A subset of the targets will be observed in longer integrations to detect high-contrast binaries. CAMERA's excellent near-infrared (NIR) image quality will allow us to detect low mass brown dwarfs in few-minute integrations [4] for these nearby targets. In addition, CAMERA's dense actuator spacing (less than 14 cm projected onto the primary mirror) will reduce speckle noise and so improve the contrast ratios that can be achieved.

Stars down to $m_V = 19$ can be observed as on-axis tip-tilt sources; a statistically-useful sample of the remaining few low-mass and white dwarf stars will be obtained in the infrared using off-axis tip-tilt stars. Candidate companions will be re-observed for common proper motion companionship confirmation and to establish the initial astrometric measurements vital to pin down the mass-to-luminosity relation [5].

This program's unprecedented high-angular-resolution sample size enables very much improved statistical constraints on the variation in binary properties as a function of mass, as well as a sensitive search for the most interesting exotic multiple systems such as close white-dwarf / brown-dwarf pairs.

3.1.2. Lensed quasars

CAMERA will perform the largest-ever search for new gravitational lenses on angular scales below 1". This survey will increase the number of known gravitationally lensed quasars (and measured time delays) by almost an order of magnitude. More important, this sample will have a homogeneous selection criterion. A large homogenous sample of such systems will be a unique tool to study key issues related to galaxy mass distribution, mass evolution, dark matter content, and mass-to-light evolution, as well as the size and structure of quasar accretion disks. 90% of all systems will have angular separation smaller than about 1.5", which requires high angular resolution. CAMERA will perform high resolution H-band imaging of all quasars with z > 1 and i < 20.0 mag for which a suitable tip-tilt star is present. H-band imaging is optimal for detection of the lensing galaxy as well as the quasars.

To have an excellent chance of detecting most components of likely lens geometries (e.g. the equal-magnitude sources in Figure 5) CAMERA will require approximately 300-second integrations. Selecting likely targets from the seeing-limited SDSS survey will yield around 25,000 candidate targets. Observing about 90 candidates per night, this survey can thus be completed in approximately 9 months spread over the 5+ year lifetime of the CAMERA system. We estimate that this search will yield 300-700 new lensed quasars suitable for time delay measurements. The follow-up monitoring program will require approximately an additional 3 nights per month, selecting the brightest of the newly discovered lenses for increased SNR.

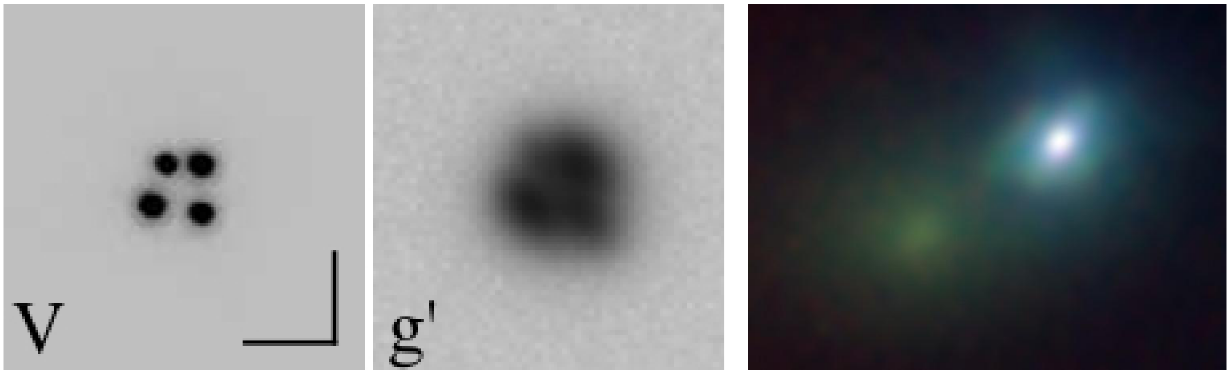

Figure 5. *(Left and Center):* The gravitational lens HE 1113-0641 [6]. In V: HST image. In g': Seeing-limited discovery image, taken in exceptional seeing. High angular resolution observations were required to confirm the lens properties, search for the lens galaxy and photometrically separate the images. Observations taken in standard seeing would have failed to resolve this lens. *(Right):* Supernova 2006GY [7], the second-most luminous supernova ever recorded. Lick AO observations were required to separate the supernova from its host galaxy and ascertain if it was simply AGN variability. The AO observations rapidly confirmed the nature of the transient and gave vital information: position in the host galaxy and a light curve resolved from the bright galaxy nucleus. The ability to quickly and inexpensively perform such observations is growing ever more important as surveys begin to find many potentially interesting transients every night.

3.1.3. Asteroid binarity

After searches of relatively small numbers of targets, AO and HST observations have found tens of companions to asteroids and Kuiper-belt objects [8]. A much larger sample of systems is required to fully investigate the frequency of companions among different asteroid populations and disentangle their different formation mechanisms. CAMERA is well suited to execute the deepest-ever survey of asteroid multiplicity. Its 80 mas visible-light resolution is sufficient to resolve 120 km separation multiples at the center of the main belt and 250 km systems in Jupiter's Trojans. Nearly half of all currently detected companions are at separations > 100 km, so we expect CAMERA could discover many new and interesting systems.

3.1.4. Large M-dwarf Astrometric Planet Searches

The higher-mass M-dwarfs that have been probed up to now have a low Jupiter-mass planet companion frequency (<2%; e.g. [8,9]), but theorists predict a large population of lower-mass planets (e.g. [10,11]). The characteristics of the lower-mass M-dwarf planet population are essentially unknown, mostly because the stars are too faint for current optical RV planet searches. As M-dwarfs are the most common stars in our galaxy, there is a clear gap to be addressed in our knowledge of the galactic planetary population; a detailed understanding of planetary statistics at the low end of the stellar mass scale will provide vital new constraints for planet formation theories.

Two new technological breakthroughs – sub-milliarcsecond adaptive optics astrometry and CAMERA's low-cost adaptive optics system – would provide an unmatched M-dwarf exoplanet detection and follow-up capability. Unlike transit surveys the astrometric planet detection program will be able to search for planets in all orbital orientations, giving a more complete picture of the planetary environment of particular stars.

Cameron, Britton & Kulkarni [13] recently discussed the problem of differential AO astrometry in the face of the dominant noise source (which is correlated tilt anisoplanatism), derived its expected contribution to our astrometric uncertainty from theory, developed an optimal estimation algorithm for performing astrometry, and verified the expectations with extensive on-sky tests at Palomar and Keck. Test targets achieved ~100 microarcsecond precision in 2 minutes with ~100 microarcsecond accuracy over 2 months. As discussed in detail in a 2010 decadal survey white paper [14], a CAMERA-equipped small telescope could achieve similar precision in long integrations using the same techniques.

An M-dwarf astrometric survey using 5 CAMERA-equipped 1.5m telescopes and targeting 800 late M-dwarfs allows detection of Neptune-mass planets in 10-year orbits and Jupiter-mass planets at all accessible periods (limited by the cadence of the survey). A smaller 50-star target list allows detection of ~4-Earth-mass planets around nearby M-dwarfs.

3.2. Rapid high-SNR, high-angular-resolution transient characterization

New and current transient projects such as the Catalina Sky Survey, PanSTARRs, and the Palomar Transient Factory (PTF) aim to produce thousands of new optical transients, from which the most interesting must be selected for follow-up. PTF (www.astro.caltech.edu/ptf/) has recently started science operations, and is already discovering 10s of interesting transients per night (e.g. [15,16]). There is a clear need for a facility capable of rapidly characterizing interesting transients without using costly large-telescope observing time.

CAMERA will reach the same signal-to-noise ratio (SNR) in the same integration time in the near-infrared as a 4-m seeing limited telescope (Table 2). Programs which require NIR photometry, in particular, can be executed up to an order of magnitude more quickly using CAMERA compared to a seeing-limited system on the same telescope. This is particularly important for the confirmation of higher-redshift objects. Candidate GRBs subject to the Gunn-Peterson trough are one such class of transient that will require rapid near-IR characterizations, and even moderate-redshift supernovae are only easily detectable by current surveys in their peak emission in the z’ band.

Light-curve and photometric characterization in the near-IR is extremely observing time-intensive due to the high sky brightness. Obtaining a single point of useful photometry on a z = 0.7 supernova in z-band will require at least one hour on the full Pan-STARRS array[3]. Detailed follow-up of a single high-z supernova could thus use entire nights of precious array time. These are important objects, as the greatest leverage to constrain the evolution of dark energy is found at higher redshifts. CAMERA can reach the same objects rapidly, without requiring precious large-telescope observations.

In addition to reducing exposure times, CAMERA’s high-angular-resolution capabilities can make the vital difference between simply confirming a transient and immediately disentangling its environment and answering key questions - is it hosted in a faint galaxy? (Figure 5) Is it really associated with a precursor noted in HST images? Is there any contamination in its light curve from nearby sources? (Figure 6)

Although CAMERA’s high-Strehl (>25% at H-band) sky coverage is ~30%, the transient rate is sufficiently high that the system could be kept fully occupied by events that fall close to tip-tilt stars; PTF alone is producing many new interesting transients each night and requires at least 10 multi-color observations per transient. Full infrared characterization and light-curve measurement of large samples of distant transients thus becomes practical and affordable with CAMERA.

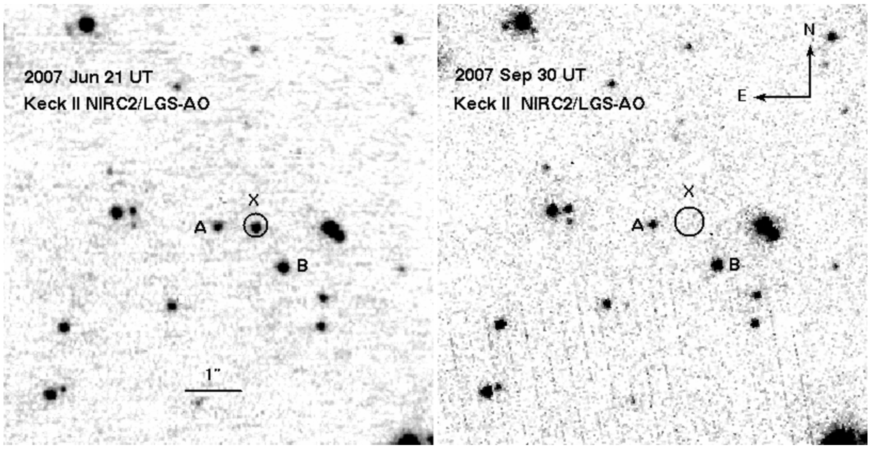

Figure 6. Swift J1955+2614, one of the strangest transients of recent years [17-19]. This galactic transient was discovered in the galactic plane by the Swift Gamma-Ray-Burst detector satellite. Follow-up observations revealed an extremely complex (and still poorly understood) light curve, followed by rapid fading. Since stellar crowding was significant, LGS-AO observations were required to separate the transient light from surrounding stars. (Left): The transient during emission. (Right): the transient location after emission ceased. Note the 1” scale bar; clearly, accurate photometry of this very interesting source required high-angular-resolution observations. CAMERA could easily perform similar observations within minutes of initial detection.

3.3. Monitoring

CAMERA provides the high angular resolution required to detect spatially-resolved changes early in transients’ evolution. The advantage of high resolution is illustrated by the spectacular images of such objects produced by the Hubble Space Telescope (e.g. [20]). CAMERA is able to periodically return to the sites of transient events to monitor photometric changes, spatially-resolved outflows or even light-echoes. Required integration times vary

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[3] Pan-STARRS science case: http://pan-starrs.ifa.hawaii.edu/public/science-goals/active-universe.html

greatly depending on the object and distance, but under all circumstances it will be much preferable to conduct the initial identification of evolving objects with CAMERA rather than HST or any larger and more expensive LGS AO-equipped telescope. CAMERA is particularly useful for high-angular-resolution monitoring applications, with queue scheduled operation allowing individual targets to be easily re-observed night after night. Routine monitoring of other targets, such as solar system objects, can also be pursued.

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