High-angular-resolution, high-contrast adaptive optics at Palomar Observatory

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Abstract

Caltech Optical Observatories and its partners are pursuing a vigorous program of laser guide star (LGS) adaptive optics on the 5-meter diameter and other telescopes at Palomar Mountain. A full year of commissioning photoreturn results from the University of Chicago sum-frequency sodium laser system is now available. In addition to LGS progress, we have demonstrated diffraction-limited on-sky NGS imaging resolution of 31 milliarcsec (152 nanoradians) using a Cambridge University fast framing, photon counting CCD camera. Leveraging our development of cutting-edge anisoplanatic PSF estimation techniques, based on $C_n^2(h,t)$ monitoring now in routine use at Palomar, we have achieved differential photometric precision well better than 1% and astrometric accuracy better than 1 milliarcsec. These accomplishments hint at the visible light science capabilities we expect to realize via a major facility upgrade planned for Summer 2010. This upgrade, known as PALM-3000, will also incorporate an AMNH-developed speckle-suppression integral field spectrocoronagraph and a JPL-developed nanometer-precision calibration unit to achieve contrast levels of $\sim 10^{-6}$, down to apparent companion magnitude of $m_V \sim 25$ in a 300 second exposure at an angular target offset of 1.0 arcsec in median seeing conditions. For 1-2.5 meter telescopes, we have successfully closed the MEMS DM-based AO loop in the laboratory, demonstrating the basic affordability of compact Rayleigh LGS systems based on our architecture.

1. Palomar AO Laser Guide Star Facility Status

1.1. *Overview*

The Palomar Laser Guide Star Adaptive Optics Facility [1] (PALM LGS) completed commissioning and has enjoyed ~12 science nights of operation through August 2007. The system is further scheduled for an additional 11 science nights in the 2008A (winter) observing semester, despite significant instrument downtime in order to prepare the optical bench for the arrival of two new AO-fed instruments (the Oxford-built visible integral field spectrograph, SWIFT, and the AMNH-built speckle-suppression integral field spectrocoronagraph, P1640, described below), in Spring 2008.

The Palomar Adaptive Optics System currently is designed compensate atmospheric turbulence at up to 2 kHz frame rates. AO performance on bright natural guide stars ($m_V < 11$) has been measured to be as good as 150 nm rms residual wavefront error (WFE), and typically 230 nm rms WFE in median Palomar conditions. Laser guide star performance has been measured to be as good as 310 nm rms WFE (using a bright, on-axis natural tip/tilt star) as of July 31, 2007. In median Palomar conditions, such LGS performance is currently more typically 450 nm rms WFE.

1.2. Measured sodium return above Palomar Mountain

Resonant backscatter return from the mesospheric sodium layer has now been measured at Palomar Mountain over approximately one year (under a variety of seeing and meteorological conditions). Transmission losses in the uplink beam transfer and launch telescope system has been carefully measured (and in fact reduced during commissioning activities), yielding a current transmission from the Coude lab at Palomar through to the mesosphere (at zenith) of 0.6 (BTO+LLT) * 0.85 (atmosphere) = 0.51.

The normalized return, in unit of photons / cm^2 / s / W are presented in Figure 1. Care must be taken in interpreting this return, as often assumptions vary. We use return fluxes (photons / cm^2 / s) that are 'unadulterated', that is the flux that would be measured at the top of the absorbing atmosphere, when pointing at zenith. Other authors have quoted this value at the top of the telescope, but this leads to confusing comparisons between systems operating at different altitudes. The Watts used here are total Watts of 589 nm sodium laser power delivered to the mesosphere, integrated over an approximately Gaussian FWHM return spot size that was a function of LLT status and atmospheric seeing. Again, atmospheric absorption, as well as all projection losses, has been accounted for to estimate the integrated power at the mesospheric sodium layer. Thus, the return values in Figure 1 would be reduced by a factor of atmospheric transmission loss squared ~0.85^2 = 0.72 if one was interested in return flux at the telescope in terms of Watts projected from the telescope.

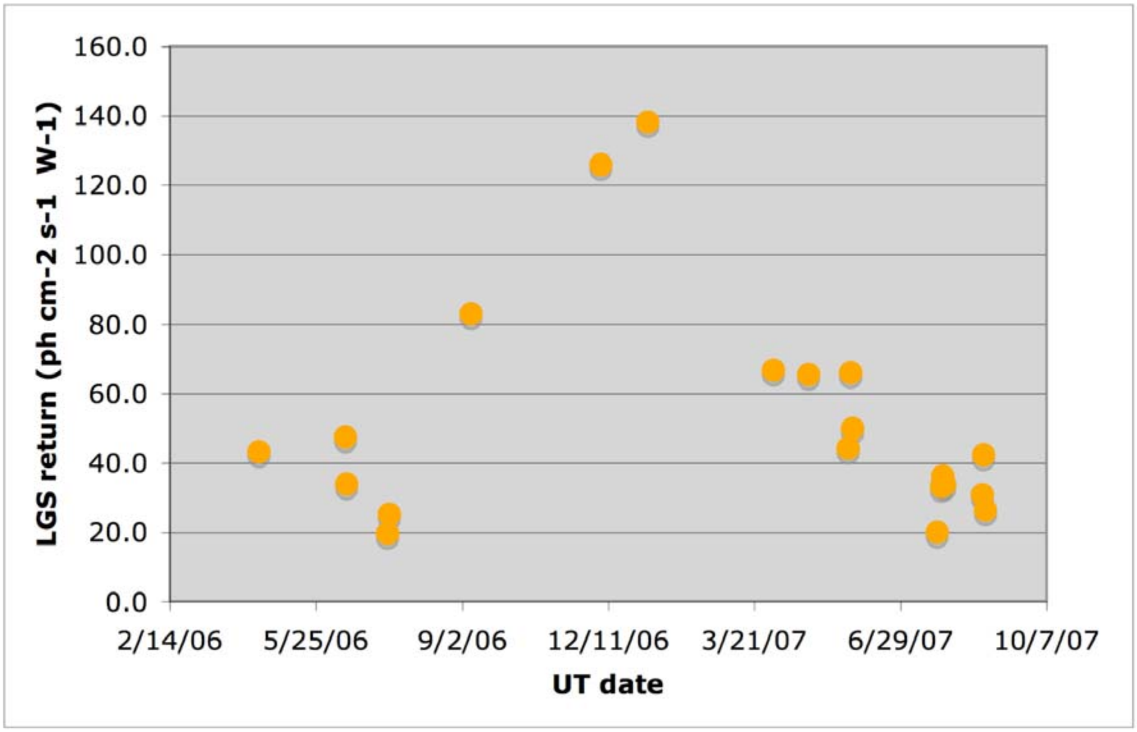

Figure 1. Unadulterated mesospheric photoreturn from the 8 W class University of Chicago micropulse/macropulse solid-state sum-frequency sodium laser. Units of return are given in photons / cm^2 / s / W of 589 nm laser power delivered to the mesosphere, as would be measured at the top of the atmosphere (e.g. with downlink atmospheric absorption effects removed). All instrumental uplink and downlink effects have been removed to ascertain return behavior of the sodium layer.

These return values appear consistent with an approximately sinusoidal annual variation of mesospheric sodium abundance, with daily fluctuations of approximately a factor of two. It should be noted that development of the University of Chicago M/M pulse laser has continued through this period, to increase power, improve operational efficiency, and in one case diagnosis of unusual power fluctuations. Power delivered to the mesosphere ranged between 1W and ~4W across these observations. The delivered laser spectral bandwidth corresponding to each observation is unknown.

2. Anisoplanatic PSF Estimation based on Continuous $C_n^2(h,t)$ Measurement

As part of the adaptive optics program at Palomar, the Observatory has installed turbulence-monitoring equipment to provide continuous, nighttime monitoring of turbulence conditions. This equipment utilizes a differential motion monitor [2] and a multiaperture scintillation sensor [3] to measure a seven layer vertical turbulence profile at ~1 minute intervals. This equipment has been placed in a telescope dome and monitors Polaris continuously. Vertical turbulence measurements and derived parameters such as the seeing, Fried parameter, isoplanatic angle, and atmospheric transparency are posted in real time on a public webpage. An example of the data view available to astronomers is shown in **Figure 2**.

These measurements are used by technical staff and observers for adaptive optics system performance diagnosis and tuning, and for monitoring scientific data quality. Measured turbulence profiles have also been used in postprocessing for prediction of the field dependent point spread function delivered by the Palomar Adaptive Optics System. These point spread function predictions have been employed to perform image deconvolution on crowded stellar fields, yielding differential photometric precision well better than one percent [4] and astrometric accuracy well better than 1 milliarcsecond [5].

3. PALM-3000 Update

3.1. Overview

Caltech Optical Observatories is developing a first-of-its-kind visible-light adaptive optics capability, PALM-3000, to be realized as a major upgrade to the existing facility 5-meter telescope AO system.

Utilizing a new 3,368-actuator Xinetics, Inc. deformable mirror (in addition to the existing 349-actuator), a 64x64 Shack-Hartmann wavefront sensor based on an E2V CCD50 detector and SciMeasure, Inc. camera electronics (running as fast a 3 kHz frame rate), and a new infrared tip/tilt sensor for increased LGS sky coverage, we expect to achieve residual wavefront errors as low as 80 nm RMS on bright ($m_V < 6.5$) guide stars and > 40% K-band Strehl ratios over > 30% of the sky with our current 8W-class University of Chicago sodium laser in an N=16 across pupil sampling mode in the WFS. Full advantage of the LGS capability of PALM-3000 could be achieved with mesospheric sodium photoreturns consistent with that report using a 20W-class CW laser at SOR [7].

The inclusion of two deformable mirrors poses challenges to both the RTC and servo control law (e.g. woofer/tweeter control.) Optical constraints result in the new tweeter mirror having a conjugate altitude at or near the primary mirror of the telescope, while the woofer mirror may optically conjugate as far as -1.5 km (e.g. well below ground.) We are actively studying this issue and hope to mitigate impact to astrometric and photometric precision.

3.2. High-contrast Science with PALM-3000

The combination of PALM-3000 and an advanced coronagraph and hyperspectral imager (hereafter called Project 1640 or P1640), under development at the American Museum of Natural History (AMNH) [8], and a precision wavefront sensor calibration unit (CAL) provided by the Jet Propulsion Laboratory (JPL) offers a broad range of research opportunities. Currently, these partners are in final negotiations on a Memorandum of Understanding (MOU) to enable this collaboration to conduct a major high-contrast survey in the Northern Hemisphere.

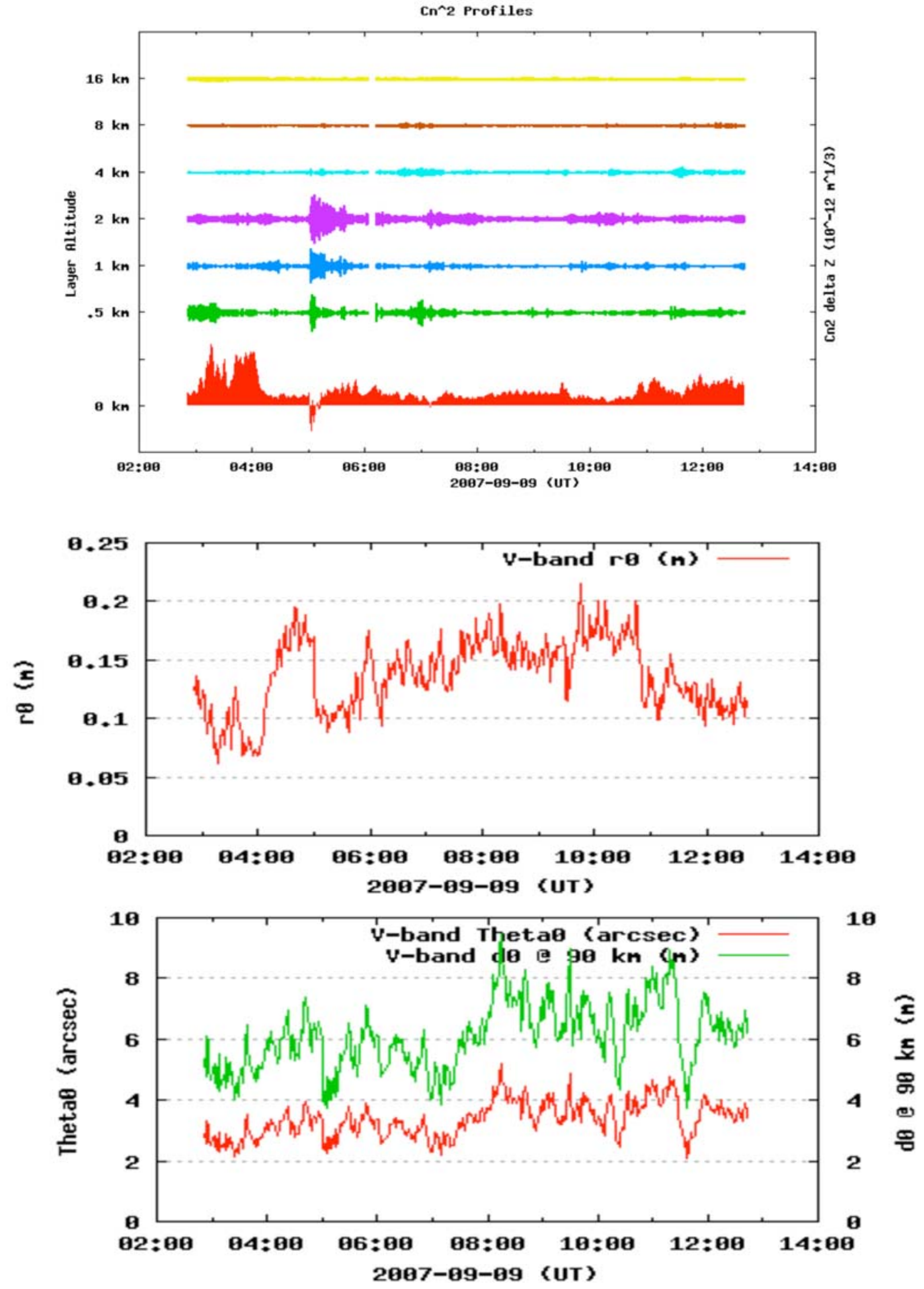

Figure 2. Example Palomar MASS/DIMM $C_n^2(h,t)$ measurement example. Top: Measured $C_n^2(h,t)$ provided by the MASS unit vs. time. Middle: Calculated $r_0(t)$ based on time series of DIMM data (not shown). Bottom: Calculated anisoplanatic angle $\theta_0(t)$, left, and focal anisoplanatism parameter $d_0(t)$, right, based on combined MASS/DIMM data.

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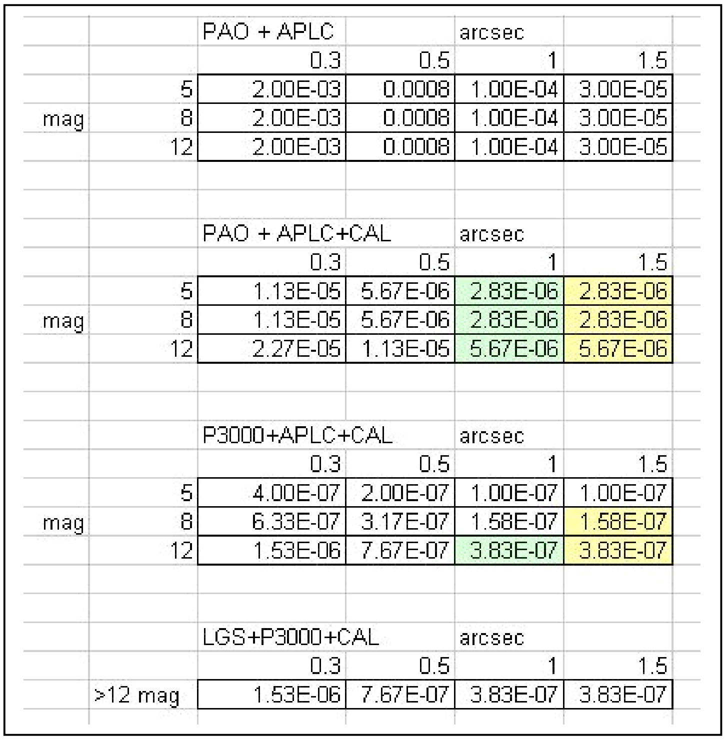
3.2.1. Science and Performance Goals

When the PALM-3000 AO system and WFS calibration system become fully operational in 2010, the P1640 stellar coronagraph is predicted to achieve a stellar suppression of $<10^{-5}$ ($\Delta H=12.5$ mag) at 0.5” separation from a bright on-axis stellar source at 1.6 μm (see Table 1). This performance will enable a search for faint, low mass companions to nearby main sequence (V < 8 mag) stars, young Jovian mass (5 M_{Jup}) companions to young stars, and imaging studies, including the possible addition of polarimetric measurements, of disks around young stars. Prior to 2010, high contrast performance will be less, as described in Table 1, for various stages of completion and for target stars of varying magnitudes.



		PAO + APLC		arcsec	
		0.3	0.5	1	1.5
	5	2.00E-03	0.0008	1.00E-04	3.00E-05
mag	8	2.00E-03	0.0008	1.00E-04	3.00E-05
	12	2.00E-03	0.0008	1.00E-04	3.00E-05
		PAO + APLC+CAL		arcsec	
		0.3	0.5	1	1.5
	5	1.13E-05	5.67E-06	2.83E-06	2.83E-06
mag	8	1.13E-05	5.67E-06	2.83E-06	2.83E-06
	12	2.27E-05	1.13E-05	5.67E-06	5.67E-06
		P3000+APLC+CAL		arcsec	
		0.3	0.5	1	1.5
	5	4.00E-07	2.00E-07	1.00E-07	1.00E-07
mag	8	6.33E-07	3.17E-07	1.58E-07	1.58E-07
	12	1.53E-06	7.67E-07	3.83E-07	3.83E-07
		LGS+P3000+CAL		arcsec	
		0.3	0.5	1	1.5
	>12 mag	1.53E-06	7.67E-07	3.83E-07	3.83E-07

Table 1. Predicted performance as a function of guide star magnitude (rows) for the combination of Project 1640, using an apodized pupil Lyot coronagraph (APLC) with the existing Palomar AO system (PAO), followed by performance of APLC + PAO with the inclusion of the WFS Calibration Unit from JPL (CAL), followed by the system with Palomar AO upgraded to PALM-3000 (P3000). A final table includes performance with a laser guide star mode in addition to all other components. Performance is in terms of starlight suppression as a function of angular separation from the star [9].

3.2.2. Project 1640 Speckle Suppression Coronagraph

The AMNH contribution to the PALM-3000/P1640 collaboration has two primary physical components: the coronagraph, and a lenslet-based Integral Field Spectrograph (IFS). The coronagraph is a diffraction-limited Apodized Pupil Lyot Coronagraph (APLC) using a ~4λ/D diameter occulting mask, a Lyot mask, and an internal 1kHz update rate tip/tilt system based on a STRAP photon counting APD quad-cell sensor. The Lyot mask will be customized to limit the diffraction from the secondary mirror and spiders on the 200-inch while the APLC design will limit the contribution of the pinned speckles to the overall speckle noise. The IFS utilizes a 200 x 200 element lenslet array and a prism spanning 1.1-1.8 microns with resolution $\lambda/\Delta\lambda$ ~30. Our focal plane will house a 2048 x 2048 pixel Rockwell Hawaii-II HgCdTe infrared detector, cooled with liquid nitrogen, which will provided by Palomar Observatory. Project 1640 coronagraph and IFS will be delivered to Palomar in early to mid 2008. Integration, testing, and initial science observations will commence immediately thereafter, subject to schedule constraints imposed by OSWIFT commissioning (if any, due to that effort in progress). Delivery by mid-2008 will allow roughly two years for installation, testing, calibration, and observations before the AO bench is taken offline for the major PALM-3000 upgrade. Integration of the P1640 coronagraph with the wavefront calibration unit (CAL) could begin as early as September 2008, subject to constraints imposed by the P1640 observation schedules. Details of the I&T schedule for P1640 and CAL will be coordinated by the P1640 and CAL co-I's, with concurrence of the PALMAO JPL Task Lead.

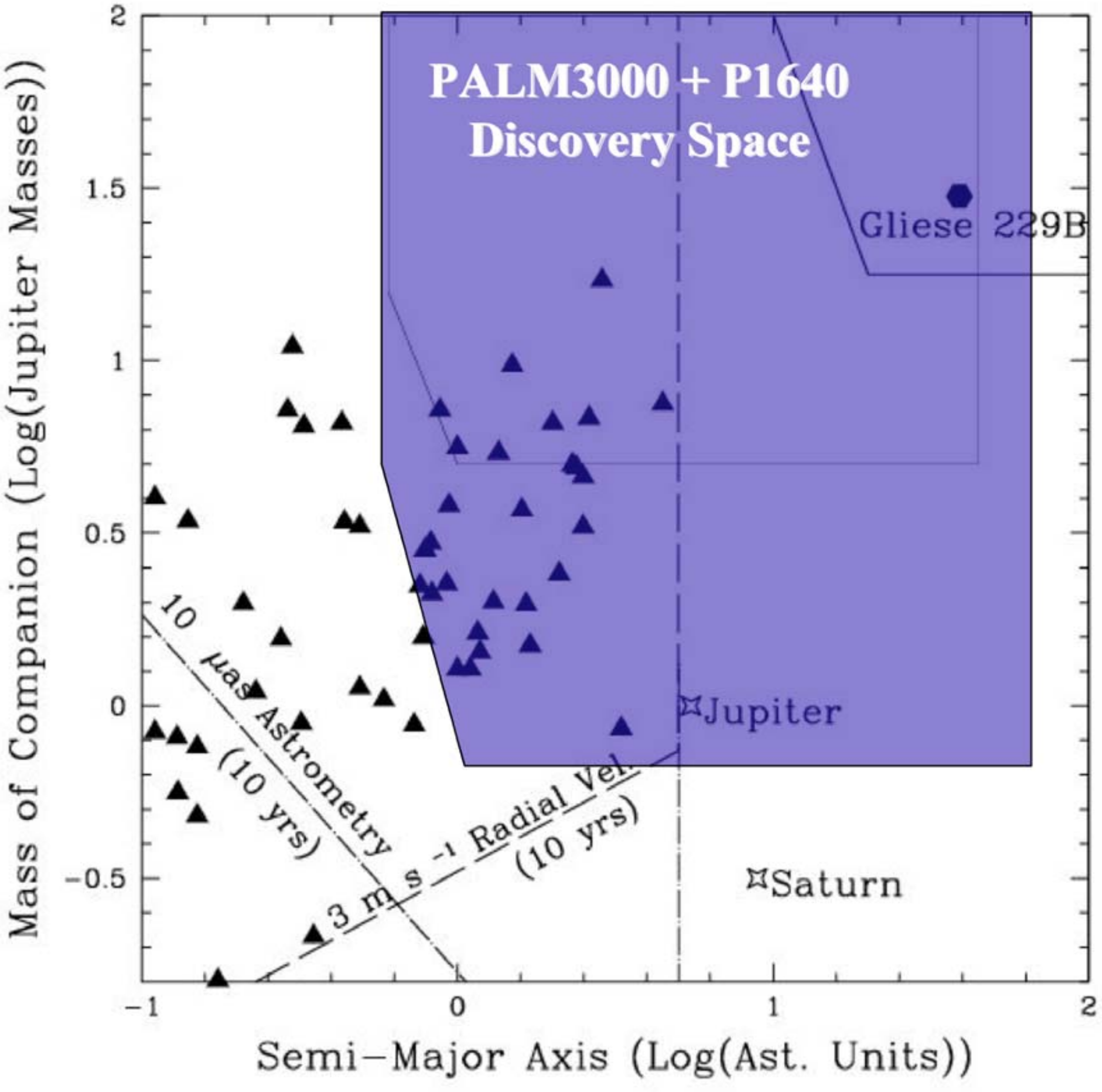


Figure 3. Planetary companion discovery space for P1640+PALM-3000 on the 5-meter diameter Hale Telescope at Palomar Mountain.

3.2.3. Precision Wavefront Calibration Unit

JPL is developing a post coronagraph wavefront sensor calibration unit for use with the PALM-3000/P1640 system. Based on a similar system developed for Gemini Planet Imager [8], the function of this subsystem is to enable the extreme AO coronagraph to realize its full potential in achieving high contrast images. An extreme AO coronagraph will typically achieve a contrast of ~1e-3 to 1e-4, at 0.2~0.3 arcsec from the star. Contrast is the ratio of the brightness of the star to the unevenness of the speckle pattern in a long exposure image. The post coronagraph wavefront sensor is an interferometer that takes part of the light at the output of the coronagraph to measure the systematic errors in the telescope/AO system optics to the nanometer level, in the presence of ~ 100nm of residual atmospheric turbulence. The goal is to improve the contrast from 1e-3~1e-4 to 1e-7. In addition to real time removal of quasi-static speckles in the coronagraph, the data from the wavefront sensor will be used in one of the approaches for post detection speckle subtraction.

3.2.4. Key Science Project

The primary project covered by this MOU is a survey of approximately 250 nearby bright stars, typically brighter than $V < 8$ mag. (depending on system performance after integration) to search for low mass companions which will likely be M stars or L & T brown dwarfs stars with $\Delta H < 10\text{-}15$ mag and orbital separations of 5-100 AU. Many of these stars are less than 1 Gyr old. Planets more massive than 2 Jupiter masses would be expected have a contrast brighter than 10^{-7}, and hence detectable. From the statistics of the ~200 known exoplanets, we conservatively expect that ~15 of our sample stars may have Jovian planets, and about 40% of them would have semi-major axes large enough to be outside of the inner working angle of the AMNH coronagraph (typically 0.2 arcsec radius, depending on the realized quality of the chromatic speckle suppression).

3.2.5. Other Science Applications

Outside of the Key Project science there will doubtlessly be considerable interest in using P1640's capabilities for studies of disks and companions of young stars as well as other targets. As many as 30 northern T Tauri and other young stars ($R < 11$ mag) could be investigated for Jovian mass companions, for example1. Disk imaging, especially with polarimetry (if implemented), will be a compelling program for optically thick disks, transition disks, and bright debris disks detected by Spitzer.

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5. References

[1] Dekany, R., *AMOS Technical Conference*, Maui, Hawaii, 2005.
[2] Vernin, J. & Munoz-Tunon, C. 1995, PASP, 107, 265.
[3] Kornilov, V. et al, 2003, Proc. SPIE, 4839, 837.
[4] Britton, M. C. 2006a, PASP, 118, 885.
[5] Britton, M. C. 2006b, Proc. SPIE, 6272E, 97B.
[6] Cameron, B., et al., 2007, in preparation.
[7] Denman, et al., *AMOS Technical Conference*, Maui, Hawaii, 2005.
[8] Macintosh, B.A. et al. 2002 SPIE 4494 60.
