Pre-observing Keck Adaptive Optics Update

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Abstract

At the time of the conference, the Keck Adaptive optics system is undergoing laboratory integration and testing, and will soon be ready for its first light on the telescope. We report on the expected and preliminary performance of the system. The testing is carried out using a turbulence generator and an artificial star, and should thus allow an accurate estimation of performance.

We also present an overview of the scientific capabilities of the Keck adaptive optics system in natural guide star mode. The small field scientific targets that will mostly benefit from the enhanced resolution of a diffraction limited 10 meter telescope will be reviewed. It is hoped that these will serve as test targets for telescope integration and scientific calibration.

1 Instrument status report

1.1 Keck AO

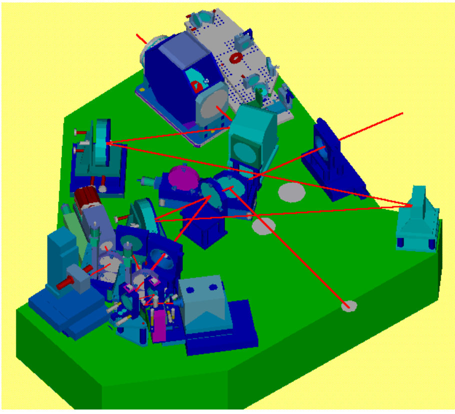

Figure 1: Drawing of the optical bench; the light comes in from the top and first goes through the image rotator (octagonal box). It is then reflected off the fast–steering mirror (tip–tilt) onto the first off–axis parabola that collimates the beam and conjugates the entrance pupil to the DM (right). After reflection on the second off–axis parabola, the beam is split chromatically towards the wavefront sensor (lower left) and the science instrument (KCam).

The Keck Adaptive Optics system (Figure 1) is a 20×20 Shack–Hartmann with a 349 actuators Xinetics deformable mirror (DM), [Wizinowich & Gleckler, 1995]. The system is mounted at the left Nasmyth platform of the Keck II telescope. The real time computer is made up of 16 Intel 860 CPUs in parallel, to cope with the large matrix multiplications involved, for such high order systems [Brase etal, 1998]. The Adaptive Optics Associates (AOA) camera uses 4 pixels/sub–aperture and has $6e^-$ read noise at a 600Hz frame rate [Brase etal, 1998].

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1.2 Rotating pupil

At the Nasmyth focus, field rotation is a function of azimuth and elevation, while pupil rotation os only a function of elevation. A derotator has been implemented, that corrects for field rotation. Since the Keck pupil is not circular, the illumination of the inner and outer sub–apertures varies with time. The rotation angle of the pupil can be computed, knowing the telescope and rotator positions or it can be determined in real time with the use of a shape recognizing algorithm. A new control matrix can be loaded on the fly, which takes into account which sub–apertures are illuminated, and which actuators are slaved. All the interaction matrices are measured and inverted beforehand.

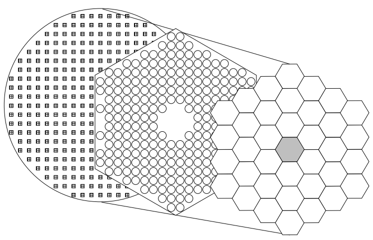

Figure 2: The Keck pupil, with the subapertures and actuator locations; The interactutaor spacing is 56 cm on the primary mirror. The actuator locations are fixed with respect to the sub–apertures, but the pupil rotates with respect to them.

1.3 Modal control

Due to the large number of actuators (producing a high sampling on the wavefront), an attempt will be made to implement modal control. It uses the approach described in [Gendron & Léna, 1994], [Gendron & Léna, 1995] – namely using a Kolmogorov model to determine the statistical covariance matrix. The eigenvalues of this matrix need to be made orthogonal on the mirror (not on the commands), so a *double diagonalisation* is used. The very high order modes are filtered out due to the high number of degrees of freedom which leads to a usually ill-conditioned system; this is due to the large range of singular values present in the system, which favors numerical errors at inversion.

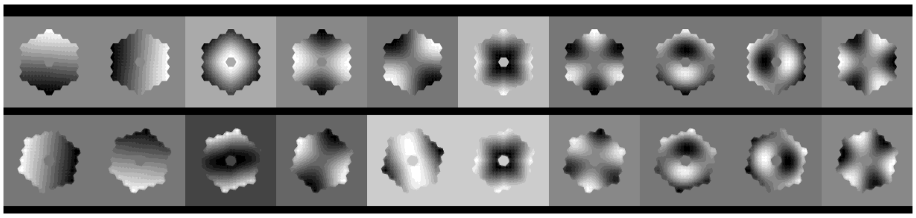

Figure 3: The Karhunen-Loeve modes for two different pupil rotations; Each time a new control matrix is loaded, the appropriate set of modes has to be determined, i.e. which sub–apertures are illuminated, and which actuators are slaved.

The modal gain optimization will be done in closed loop and real time by using the measurements and the error transfer function to estimate the signal + noise spectrum. Simulation show that this works very well for low signal–to–noise cases, while it overestimates the noise in cases when the SNR is very large. However, the optimal gain for each mode is always found. The last major difficulty we are facing is ensuring that, with hysteresis, the modes stay independent, no matter what.

1.4 Hardware

See figures 4, 5, 6.

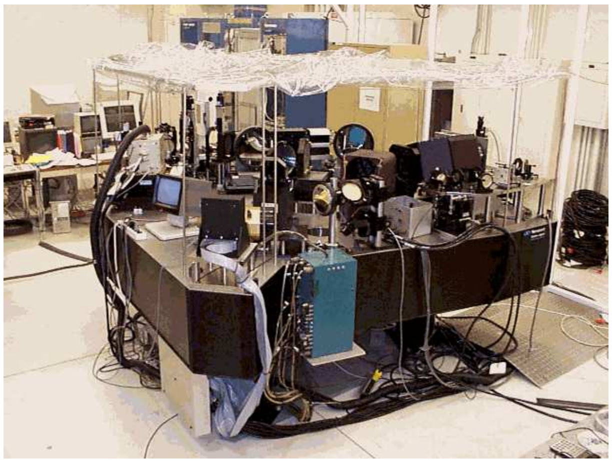

Figure 4: The AO Bench in the Waimea Laboratory. The main components are visible, with the telescope simulator on the right, and KCam and its control electronics (blue box) in the foreground. The back of the DM and the back of the AOA camera can be seen on the left.

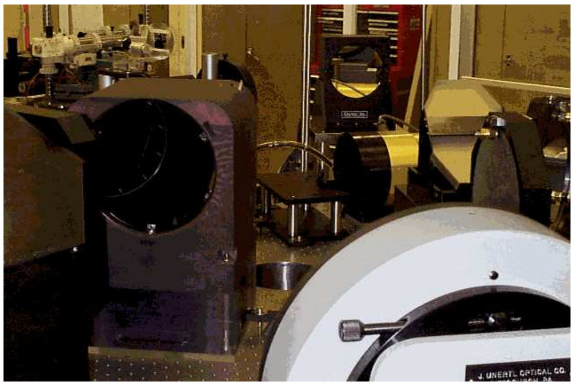

Figure 5: The active mirrors – On this view of the bench, the large mirror on the left in the foreground is the fast steering mirror; the mirror in the center of the picture (above KCam's dewar) is the 349 actuator Xinetics mirror. The large gray mount on the bottom right is the first off–axis parabola.

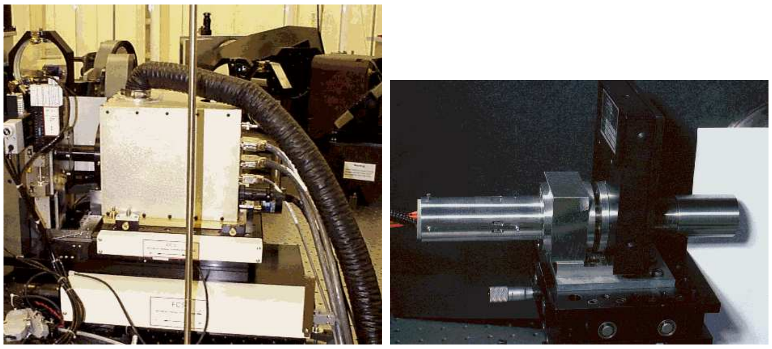

Figure 6: *left:* The AOA camera in position in the wave front sensor. The camera has many useful features, such as a video mode (helpful during alignment). The chip has 64×64 pixels, which allows for 4 pixels per sub–aperture, plus a one pixel guard band. *right:* The tip-tilt sensor quad cell head. In laser guide star mode, this will control the fast steering mirror in a separate loop, which implies that we need to filter out tip and tilt out of the DM commands.

1.5 Integration

The Xinetics mirror, and the AOA camera have been installed and aligned on the bench, and the loop has been closed successfully, with dynamic wavefront aberration present in the incoming wavefront, using a **turbulator** [Acton etal, 1998]. The power spectral density of the turbulence produced is remarkably Kolmogorov.

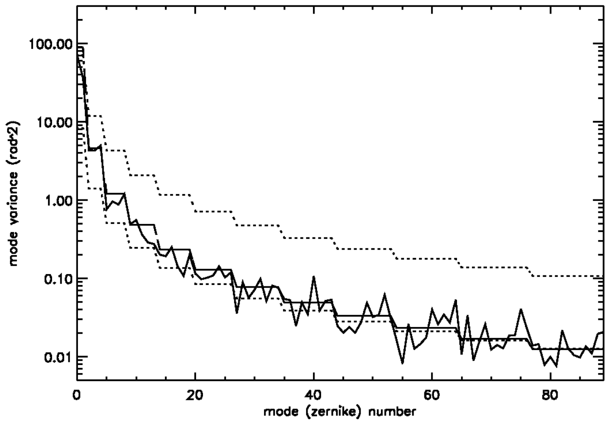

Figure 7: The spectrum of the turbulence produced by "turbulator". The full (straight) line is the spectrum of Kolmogorov turbulence projected onto the first 90 Zernike polynomials, for $\frac{D}{r_0} \simeq 40$; the dashed lines are two (poor) fits of random walk power spectra. It is clear that the best fit to the data is a Kolmogorov type turbulence.

The main difficulty in producing the right kind of turbulence lies in the fact that the pupil of the telescope simulator is 35 mm in diameter, and so, for a $\frac{D}{r_0}$ of 50 one has to fit $700 rad^2$ of turbulence in $3900 mm^2$, that is $1.8 \times 10^5 rad^2/m^2$ of Kolmogorov turbulence!

1.6 Early Science Camera

The early science detector, called KCam, is a 256^2 NICMOS III array. Re-imaging optics reduce the plate scale to allow for proper sampling in H–Band, i.e. 17 mas/pixel, producing a 4.4" field of view [Wizinowich etal, 1998]. This, of course, will have an impact on the engineering science targets.

2 Engineering Science opportunities

2.1 KCam performance

The compromise to be found for the use of KCam with Keck AO results from the high efficiency of the detector coupled to a very large collecting area, a high Strehl ratio and the limits imposed by read–out and exposure times. In zonal control, with small sub–apertures, the faint star limiting magnitude may be low. On the other hand, KCam's shortest integration times will determine a bright star limiting magnitude. This is even more true since KCam is fitted with standard J, H and K' broad band filters. We will therefore need to select science targets within a narrow magnitude spectrum, to make most of Keck AO's unmatched resolution, without loosing in efficiency due to short exposure and long read–out times (see figure 8).

2.2 Solar system

The solar system will offer many targets that will benefit from the increased resolution offered by Keck AO. For instance, the **volcanoes on Io** are very illustrative (figure 9): Speckle images obtained at Keck [Gavel etal, 1996] show what kind of resolution can be attained, yet adaptive optics images from UHAO [Roddier et al, 1991], [Roddier et al, 1998a] by [Dumas etal, 1998] show the increase in sensitivity that we will benefit from.

Another interesting target will be **Pluto and Charon**. [Roddier et al, 1998b] have observed this with Hokupa'a and easily resolved the system (the angular separation is 0.8"). The angular size of Pluto is estimated to be between

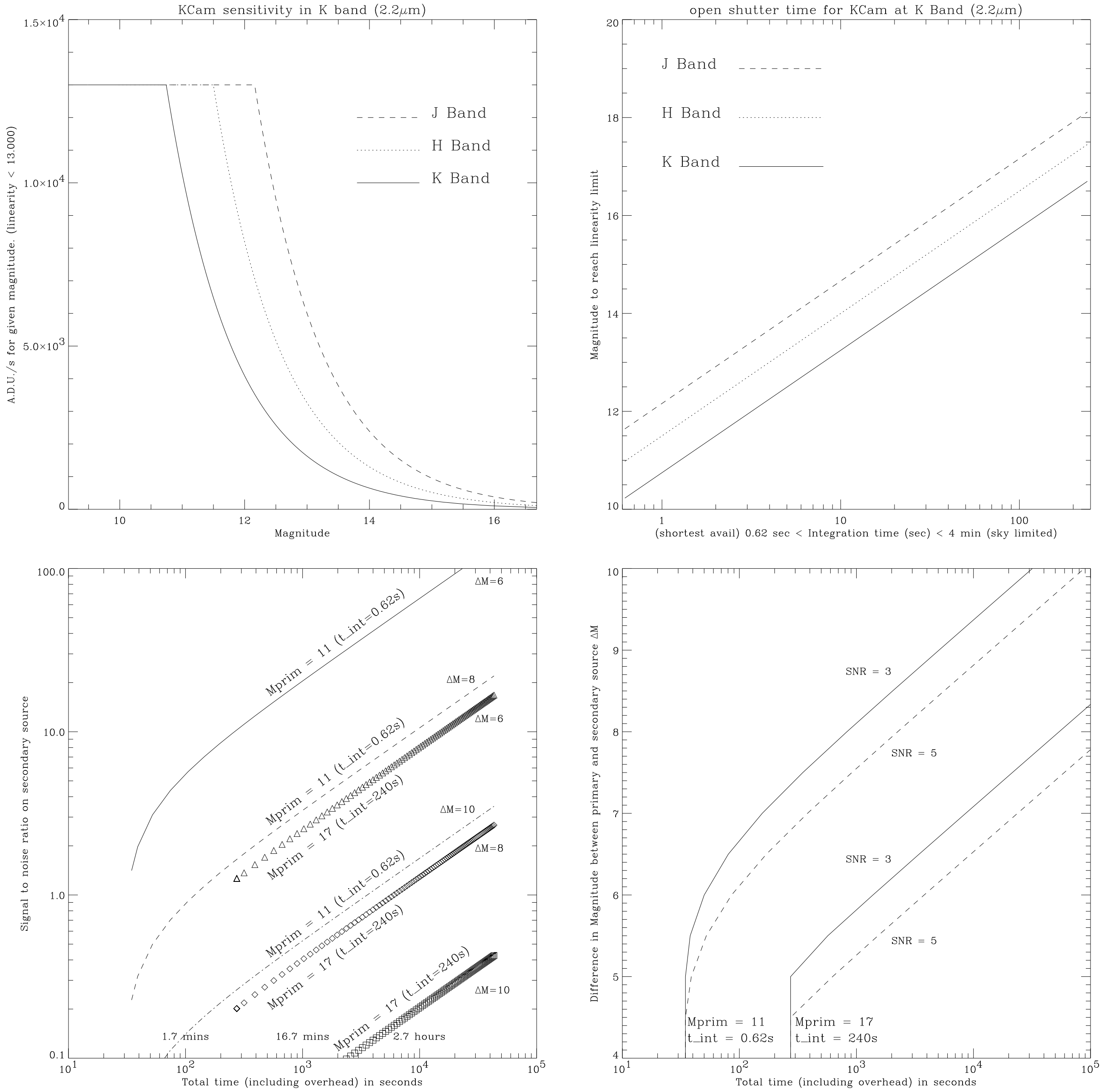

Figure 8: KCam sensitivity, maximum integration times, achievable SNR and dynamic range, assuming a Strehl ratio of 50%. The linear domain is assumed to be <13,000 A.D.U's. The read noise is 4 A.D.U's rms/pixel (and the signal is spread over 3^2 pixels). Included are photon noise and sky background noise (assumed @ 13mag/$arcsec^2$). The read time is $4 \times N_{coadd} + 30$ seconds in Correlated Double Sampling. The individual frame integration time is determined by the brightest object ($M_{primary}$) in the field.

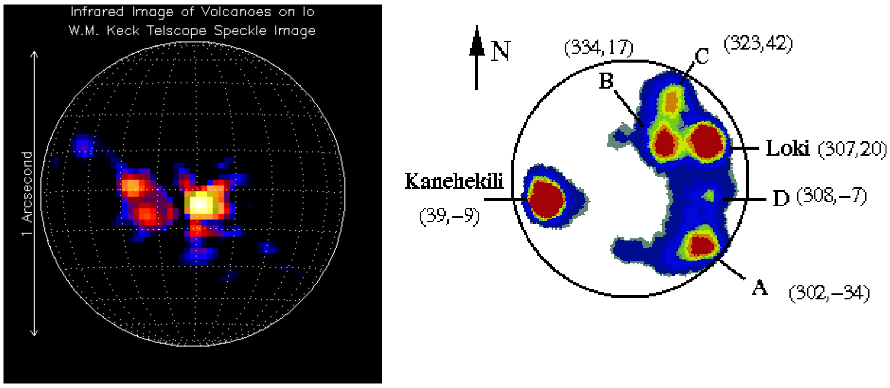

Figure 9: Io in the shadow of Jupiter as seen by the Keck telescope in speckle mode (*left*) and by the Canada–France–Hawaii telescope with the UHAO curvature–based adaptive optics (*right*). We hope to be able to combine the resolution of the former with the sensitivity of the latter.

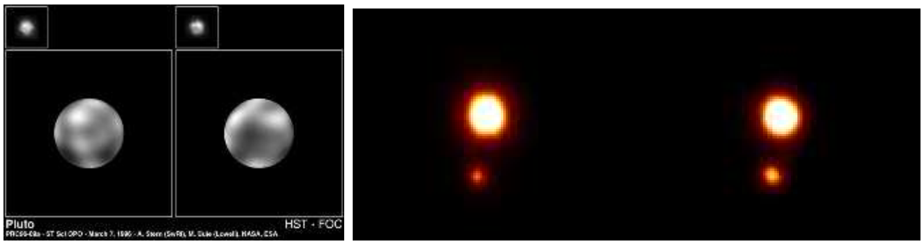

Figure 10: *Left:* Pluto as seen by HST at 200nm with the FOC. Surface features are inferred from heavy image processing, so resolved images in the near IR will allow for an interesting comparison. *Right:* Pluto and Charon as seen by the UH AO system, Hokupa'a. The pair is clearly resolved, and different albedos at different wavelengths allow to infer properties of the surface composition.

0.08" and 0.1", so it will be resolved by Keck AO. In fact, HST's FOC images [Stern etal, 1997] at 200nm has the same order of magnitude resolution (0.017") as Keck in J band (0.025"). The challenge here will be the limiting magnitude of Keck AO, as $V_{Pluto} \simeq 13.6$.

2.3 Stars and Stellar Environment

With a diameter of 49.4 ± 0.2 mas [Mozurkewich etal, 1991], **Betelgeuse** will be resolved in the near–IR. Betelgeuse is well know for its hot spots and its asymmetric structures (HST [Gilliand & Dupree, 1996] and COAST [Burns etal, 1997] images).

Binary stars are an explicit way to demonstrate the power of adaptive optics [Lai etal, 1997]. However, for this kind of imaging to be scientifically relevant, it has to be followed in time and has to be statistically significant, i.e. not very well suited to engineering time. Note that the **R Aquarii** system (figure 11) which is composed of a mass losing $\sim 1-2M_\odot$ Mira-like Long Period Variable (LPV) with a 387–day period and a $\sim 1M_\odot$ hot companion/accretion disk, has a separation believed to be between 55 mas (VLA–7mm observations, [Hollis etal, 1997]) and 0.125" (Speckle interferometry, [Hege etal, 1991]). However HST imaging [Paresce & Hack, 1994] do not resolve the binary because even if the FWHM is 0.07", everything within the central arcsecond is blurred (pre-COSTAR). What is particularly interesting is that this companion/accretion disk may be responsible for a highly collimated, supersonic bi-polar outflow (jet). It is still not understood how jets are created and sustained in a binary environment. The magnitude of this star (also know as HD 222800) is $M_V = 7.94$.

Frosty Leo will offer an exciting opportunity to study the binary system and the processes of matter ejection. It is a post–AGB star surrounded by a bipolar nebula. It has already been observed with ADONIS [Beuzit etal, 1994] and with UHAO [Roddier etal, 1995], yielding the superb picture shown in figure 12. It is well within the range of

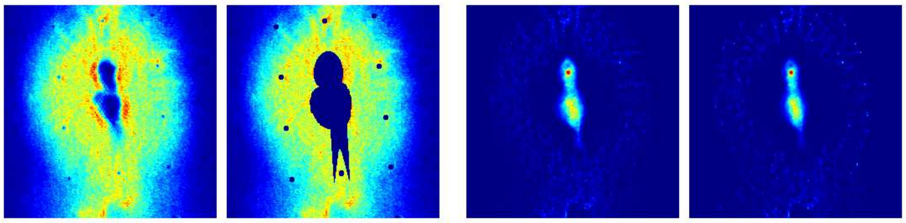

Figure 11: The R Aquarii double system. The two images on the left are the raw FOC data (saturated, so the invalid data is masked out on the image on the right), with a field of view of $0.7'' \times 0.7''$. The two images on the right illustrate the power of deconvolution, as they are the result of maximizing the entropy of the images on the left: on the left, 1000 iteration of ME, on the right 35 accelerated ME iterations [Biggs & Andrews, 1997]

Keck AO with a visual magnitude around 9 to 10, but may be too bright for KCam, with a J and H magnitudes of 8.2 and 7.7, respectively.

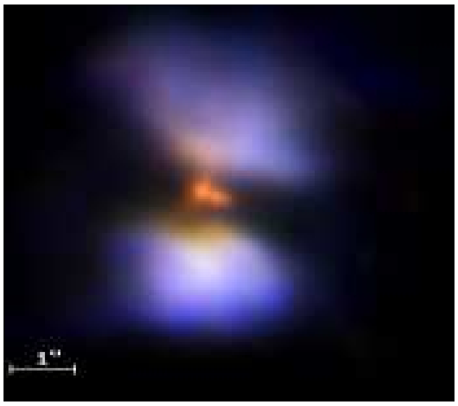

Figure 12: The Frosty Leo nebula as seen by UHAO; increased resolution on this object will allow us to discern more clearly the paths that matter follow to reach the lobes.

2.4 The Galaxy

Galactic Center? The **galactic center** will probably not be an early target due to the large distance to the rather faint guide source used by PUEO [Rigaut etal, 1998] at CFHT (magnitude 14 star located 23" away from SgrA*). Also, with a high degree of correction, the isoplanatic angle will be smaller.

Orion and star–forming regions? Observation of HST's "**proplyds**" (figure 13, [McCaughrean & O'Dell, 1996]) in Orion seems to be a very original and rewarding target. Observationally, this requires finding a guide star (the trapezium stars might be close enough to some of the proplyds?). Scientifically, this seems like a primary target: it will allow us to see the proplyds in the IR where the nebula is transparent, and hence look for morphological features that might indicate the presence (or not) of planets in formation (warped disks, etc.).

2.5 Extragalactic Astrophysics

Due to the limiting magnitude, few sources will be observable until the laser guide star becomes available. However, the sources that are bright enough will benefit tremendously from the increase in resolution. The two "classic" active nuclei **NGC 1068** [Rouan etal, 1998] and **NGC 7469** [Lai etal, 1998] will be very good test objects to see how the system behaves in partial correction; furthermore, recent results by PUEO on both these objects are starting to

Figure 13: *Left:* The trapezium in Orion, as seen by HST. The bright stars in the trapezium could be used as reference stars. Right: Example of a *proplyd* (proto-planetary disk), being destroyed by the UV radiation of the young, bright stars of the trapezium. Note that some of the disks are not being destroyed because they are further away from the stars (but closer to us) and thus the disk is dark as it obscures the HII emission behind it.

pinpoint the structures around the AGN, in the form of mini–spiral arms. Increased resolution could be necessary to confirm these results.

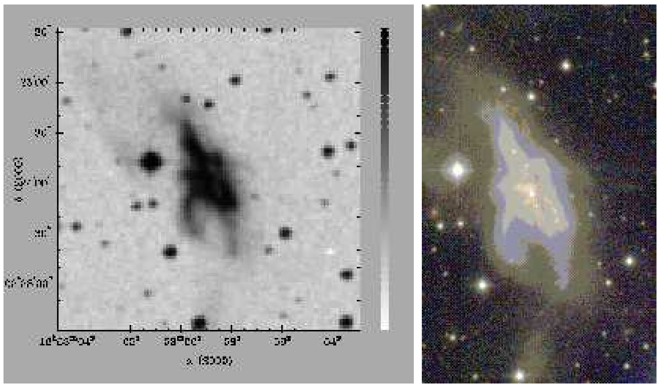

Figure 14: **Fig 15 :**The merging galaxy NGC 6240. The galaxy itself is faint, but note the star (around magnitude 12) situated around 30" North and East of the nucleus (north is up and east to the left). (The image on the left comes from the Digital Sky Survey, the one on the right from the AAT).

There are also other extragalactic objects that could serve as engineering targets, for example, the merging galaxy **NGC 6240** (figure 14) has a relatively bright star (12< M_V <13) at a distance of about 30". This could be used to test off axis correction.

2.6 Laser Guide Star Science

The extragalactic possibilities of Laser Guide Star (LGS) AO are really limitless, and many unique observations will be carried out with it. For commissioning of the LGS facility, there are some very beautiful results to be obtained on some sample objects:

Amongst the gravitational lenses, **Einstein's Cross**, or a **gravitational arc** that could be resolved across its transverse direction, with sufficiently many elements of resolution to reconstruct the underlying galaxy would undoubtedly be very impressive.

Also, **Arp 220** is an Ultra Luminous IR galaxy that is still just beyond the reach of HST and NICMOS, as the resolution (of a 2.4–meter telescope in the IR) is not high enough to understand this object.

3 Conclusion

We have presented an update on the hardware of the Keck Adaptive Optics system as it is nearing completion prior to integration on the telescope. The loop has successfully been closed in the laboratory with a turbulence generator. We have also presented a selection of sources that will most benefit from the increase in resolution provided by the Keck AO system, with the added constraints of the limiting magnitude and hence small sky coverage of the pre-Laser Guide Star system and the small field of view provided by KCam.

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