Astronomy with adaptive optics: experiences from the University of Hawaii AO program

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ABSTRACT

The University of Hawaii adaptive optics (AO) group has been actively carrying out astronomical AO observations for the last four years. The UHAO group and our collaborators have utilized the curvature AO system to obtain diffraction-limited images of asteroids, planets, moons, protoplanetary disks, young stars, young star clusters, planetary nebulae, black holes, galaxies, and quasars. The current scientific capabilities of the new 36-actuator Hokupa˙a AO curvature system will be briefly reviewed. Four key astronomical situations that are excellent for AO observations will be discussed. Examples of scientific observational techniques and limitations will be highlighted with actual AO astronomical results.

INTRODUCTION

The University of Hawaii AO program has been actively doing astronomical observations with adaptive optics since early 1994. The instrument has evolved from an experimental Coude prototype curvature system, to a highly-productive 13 actuator cassegrain curvature instrument (UHAO; Roddier et al. 1991). Now we have upgraded to a powerful 36 actuator AO system (Hokupa˙a -- "immovable star" in Hawaiian). Hokupa˙a utilizes an excellent 1024x1024 IR Camera (QUIRC) and our 1024x1024 CCD. The system achieves diffraction-limited imaging (and imaging polarimetry) at I, J, H & K in median 0.7" CFHT seeing with a R=12 guide star (resulting in Strehls from 0.3-0.6 from I-K' bands). A full technical description of the Hokupa˙a system is given elsewhere (Graves et al. 1998), and so we refer the interested reader to that paper for a complete description of the Hokupa˙a system and performance.

In this paper we will review four common scientific scenarios for our AO program. These are not the only scientific uses for AO by any means, but they do represent the majority of the situations encountered so far by our group over the last four years of taking astronomical data with adaptive optics, and so we feel a review of these 4 cases merit a brief review. It is important to point out that a very informative and comprehensive review of our AO program, published scientific results, and images exist at our new web site (*http://www.ifa.hawaii.edu/ao*). Please visit this site to view the AO images referenced in this paper in high-resolution color. *Since this web site contains all the images referred to in this paper we do not reproduce any the science images here for the sake of clarity and brevity.*

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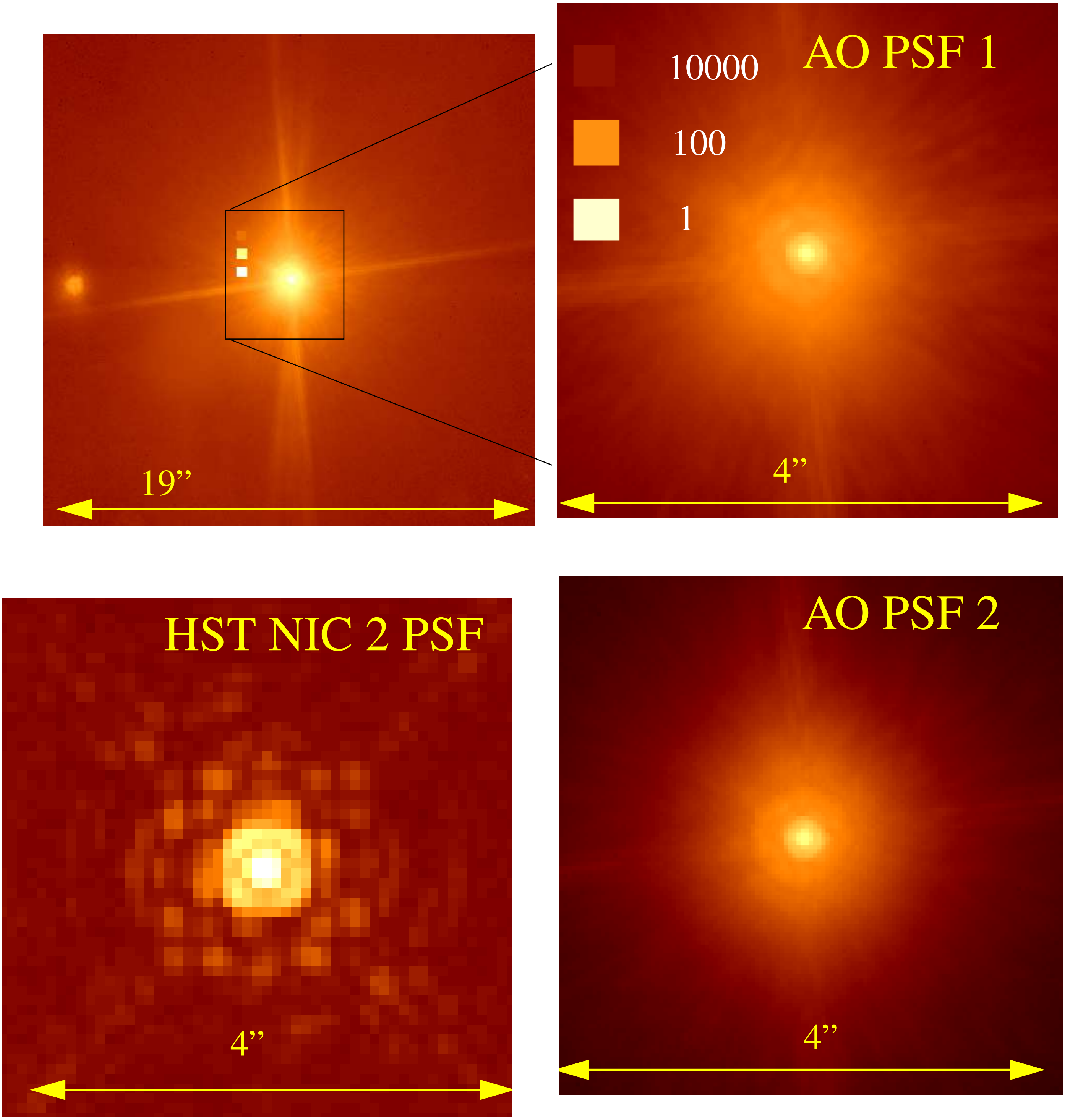

Figure 1: A comparison of two typical deep (18 min) PSFs in the J band taken with Hokupa˙a in 0.7” seeing. Table 1 outlines the PSF characteristics. The small square boxes show how sharp the PSF is by showing the change in intensity in linear units. Note the close match of the shape, smoothness, and FWHM of these two PSFs. Such PSF quality is required to detect faint disks, galaxies, or companions in astronomical applications. The PSFs have deep log stretches to highlight the faintest features. Note that PSF 1 is a m_V=8 star and PSF 2 is a fainter m_V=10 star --hence PSF 1 is brighter than PSF 2-- but the PSFs are still similar.

The PSF in the lower right hand side is a narrowband (1.8 µm) PSF taken with the HST NICMOS 2 camera. Due to the very complex NICMOS pupil the PSF is very complicated. In addition, the diffraction pattern changes with focus as HST “breathes” (Krist 1997; see his fig6). Because of this complex, somewhat unstable PSF we argue that the smoother, sharper (4m vs. 2.4m telescopes) AO PSF is better for some scientific tasks than HST NICMOS. All the above images have the same log10 stretch.

1. Faint extended Structure around bright point sources: Protoplanetary disks, quasar host galaxies and companions

The key requirement for an AO system to produce scientific results is a stable, consistent, reliable, time-independent point spread function (PSF). If a curvature AO system possesses enough actuators and stroke to eliminate the static deformations of the optics (e.g. trefoil), and enough bandwidth to remove the majority of the low-order atmospheric terms, then a stable, smooth, diffraction-limited PSF will be obtained from a curvature system. Such a stable PSF is crucial to reliably detect any faint resolved structure (either though deconvolution or simple PSF subtraction).

Table 1: Statistics for the PSFs in Fig. 1

Parameter	AO PSF1 (1.2 µm)	AO PSF2 (1.2 µm)	HST NIC 2 narrow band 1.8 µm
FWHM	0.091”	0.093”	0.18”
Strehl	0.33	0.37	0.7
exp. time	13.35 min	18.25 min	16.7 min
dynamic range at 2”	2.1×10^6	2.4×10^6	2800

To illustrate that we can routinely achieve such a PSF, we present very deep (20 min) 1.2 µm (J Band) PSFs obtained by Hokupa˙a from the first light run in November 1997 at the 3.35m CFHT on Mauna Kea. Even though these two PSFs in Fig. 1 were taken 20 min apart and on different parts of the sky they still are very similar, diffraction-limited, smooth PSFs. As Table 1 shows the Strehls and FWHMs of both these images are very similar. In fact, these PSFs are so stable that resolved structure (like a protoplanetary disk) can be detected within 0.6” of the core --even if it is 10,000 times fainter than the central star itself! This is new level of sensitivity for ground-based observations for low light level detection of extended sources near bright point sources. This ability allows Hokupa˙a to detect faint scattered light from forming solar systems around young T Tauri stars. Such disks have been detected around the single T Tauri stars HL Tau and GM Aur (Close et al. 1997a) and around binary T Tauri stars GG Tau (Roddier et al. 1996) and UY Aur (Close et al. 1998). From these faint scattered light images we gain unique insights into the nature, and size of the dust grains in these disks -which in turn acts as constraints on stellar/planetary formation theories. See C. Roddier’s paper in these proceedings for more detail about Hokupa’a observations of T Tauri itself.

We gain further insight into these protoplanetary disks by imaging-polarimetry with Hokupa˙a. Hokupa˙a has obtained deep 2hr polarimetry J-Band images which are able to detect a clear polarimetric map of the disk around the UY Aur binary. This is particularly impressive since the disk is 100,000 times fainter than the central binary at a separation of only 2”. Moreover, to produce the centrosymmetric polarization pattern observed requires that the PSF not vary significantly between the 4 polarization images -each 0.5 hrs long! This is the first time a T Tauri disk has had a polarization map measured, and from this map we can place more constraints on the dust grain population and be for the first time confident that flattened dust disks surround these young stars. See D. Potter’s paper in these proceedings for more detail.

Another extremely interesting scientific project is the imaging of the host galaxies around quasars. This is a similar problem of faint extended emission around a brighter point-source. The difference is that the QSOs (R~16) are usually much dimmer than the T Tauri stars. However, the use of zero read-noise APDs (avalanche photodiodes) in Hokupa˙a's curvature wavefront sensor (WFS) allows guide stars as faint as 16-17th magnitude to be used (without slowing down the WFS sample frequency). We were able to obtain sharp images in a 2 hr J band image (and a separate 1.5 hr H band image) of the QSO PG1700+518. These images show how even guiding on a R=16.5 QSO it is possible to produce 0.28" FWHM images (uncorrected seeing was 0.7"). These images allowed the first clear detection of the structure/morphology of the QSOs faint companion galaxy (see Stockton, Canalizo, & Close 1998 for more details).

2.0 Faint Companion Detection: New binary systems, cluster surveys

The next class of science observations that we have carried out is the detection of faint point sources near brighter points sources. Here PSF stability and smoothness are also critical to scientific success. However, it is also important to maximize the enclosed energy (EE) in the core of the PSF as well. Hokupa˙a's ability to enclose 30% of the PSF energy inside 0.07" (at I and J band) enables a faint companion to "pop" up above the noise of the PSF from the brighter primary. In this manner with 0.093" FWHM images and Strehls of 0.37 Hokupa˙a can detect a star 2000,000 times fainter at a distance of 3.0" in 6 min at J. At smaller separations the PSF noise from the primary is much higher and so only companions 500 times fainter can be detected at 0.5" (see Fig. 2). The sensitivity decreases even faster once the airy rings from the secondary mirror shadow and primary are reached. Once, inside the FWHM resolution it becomes possible to only split equal magnitude binaries, and the sensitivity to fainter companions rapidly diminishes.

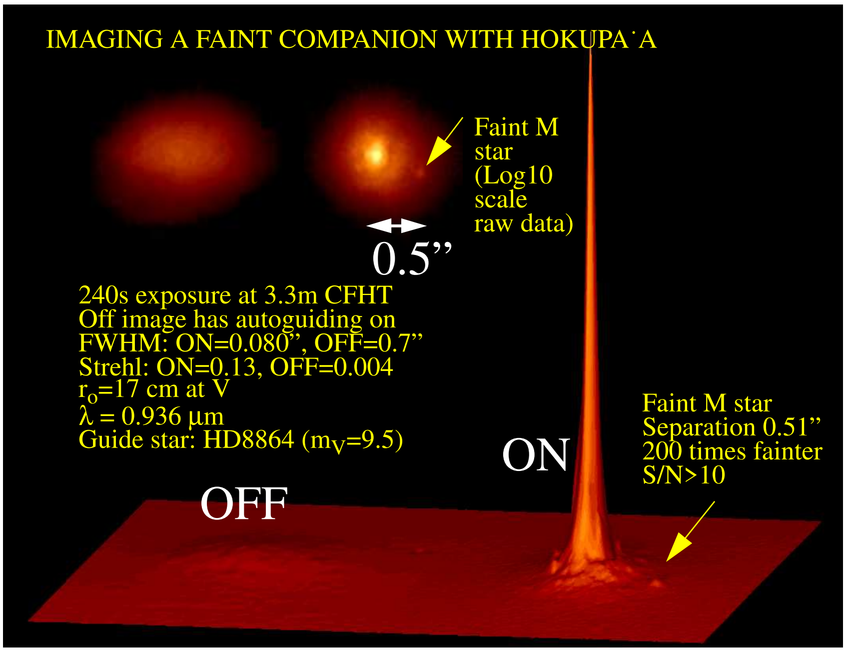

Figure. 2: Here we show the ability of Hokupa˙a to detect faint companions very close to much brighter stars. The above images are narrow I band images showing the first detection of a faint M star just 0.51" from a star 5.7 mag (200 times) brighter. Other images from Hokupa˙a show the detection of a M8V star *15 mag fainter* at distances of 3".

To show in some detail how binary detection sensitivity is affected by distance and wavelength we have plotted in Fig. 3 the sensitivity derived from our observed PSFs at J. The curves illustrate the maximum flux difference between the primary and its companion as a function of separation. The companion flux is defined as the 3σ noise of a 0.07x0.07” patch of the PSF. The total flux of the companion is determined by enclosed energy of the PSF inside 0.07”. In other words, if at 0.5” the primary’s J band PSF 3σ noise is 1/1000th its total flux, then it is clear that a companion 1/100th the flux of the primary could be detected at the 3σ level if the PSF’s EE=10% inside 0.07”. Once inside the FWHM, sensitivity must be calculated by a PSF subtraction algorithm.

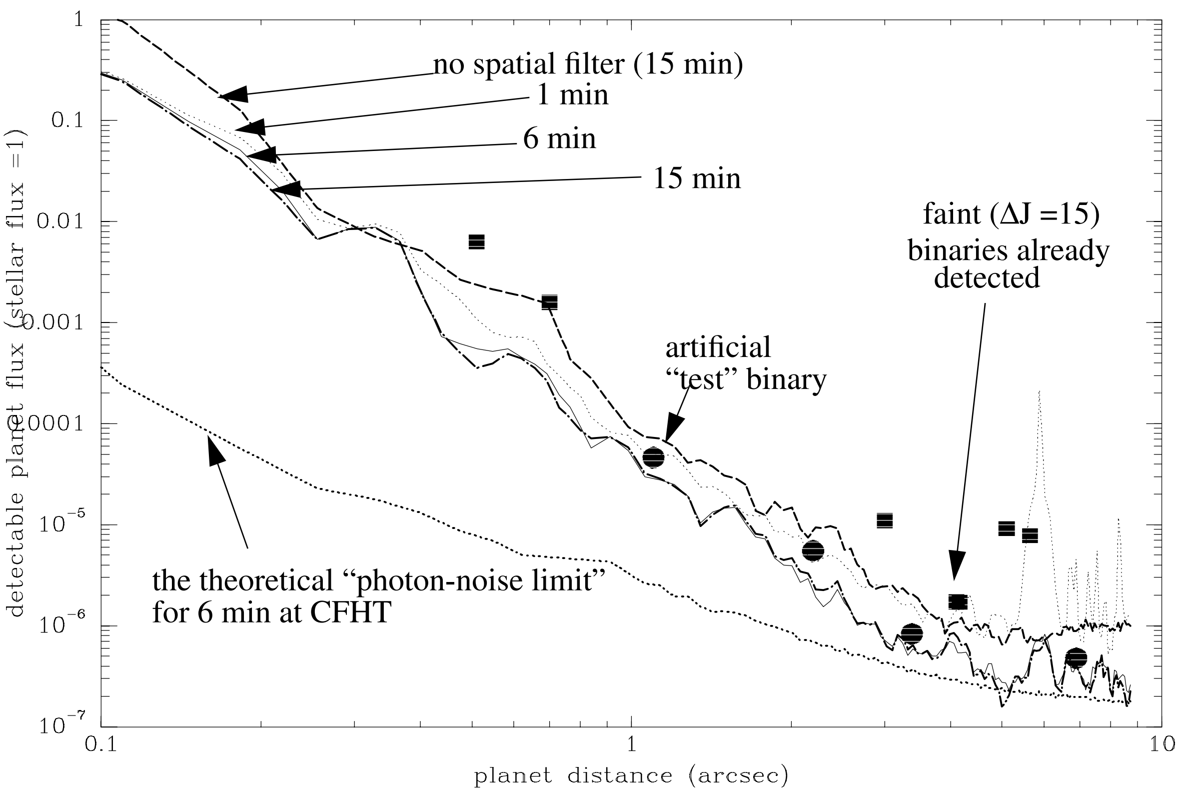

Figure 3: Hokupa`a’s point source detection sensitivity to 3σ detections of faint companions (called “planets”). The curves are based on the observed J PSF at CFHT. The solid squares mark selected binaries discovered by Hokupa`a at first light (at J in 6min exposures). The solid circles mark artificial sources that were recovered at the 3s level from the data -giving confidence to our technique for estimating the sensitivity of the AO PSF. The first “dip” in sensitivity is due to the first airy ring the second big dip is due to the CFHT central obscuration. A slight improvement is gained by a spatial filtering technique, but increasing the exposure time beyond 6 min fails to increase the sensitivity inside 2” due to the “fixed” pattern noise produced by the “super speckles”. Only at radii of 2” or greater is the sensitivity “photon-noise limited”.

Several dark squares mark selected *real binaries resolved with* Hokupa`a which show the curves are very realistic. It is also important to note that none of this analysis uses deconvolution or any PSF removal --this is just raw data. Higher sensitivities can only be obtained (inside 2”) by better determination of the “fixed-pattern noise” produced by the “super speckles”. Beyond 2” longer integrations reach higher sensitivities as root exposure time.

It is critical to minimize the FWHM and maximize the EE. Hence, observations at I band with FWHM=0.067” and EE=27% @ 0.07” are much better than K’ observations with FWHM=0.13” and EE=21.8% @ 0.07” (even though the I Strehl is 0.3 and the K Strehl is 0.6). In fact, I band searches for companions will be 16 times more sensitive than K band searches from 0.1"-0.3" separations. At larger separations (sep>>FWHM) the sensitivity difference between wavelengths decreases.

It is also interesting to note that our current J-band imaging at Strehls of 0.3 is very close (within a factor of 2.5) to the theoretical sensitivity that would result from a Strehl=1.0 "perfect" PSF (top curve), hence higher order systems would not greatly improve our sensitivity at I band or longer wavelengths (higher order systems would of course dramatically improve our shorter wavelength performance at R and V).

It is interesting to note just how much difference AO makes to the binary detection problem. In the case of *no* AO correction (at J band, FWHM=0.6", EE=1% @0.07") the use of Hokupa˙a increases CFHT's sensitivity to binaries by a factor of 250 from 0.2"-0.5" separations! The detection of faint companions is an ideal problem for AO correction since it provides a bright guide star, the companion is inside the isoplanatic patch, and the sharp diffraction-limited core of the companion can penetrate the uncompensated gaussian halo of the primary PSF with ease.

It is also interesting to note how ground-based AO can have superior sensitivity to HST's NIC 2 camera. The primary reasons for this that the AO PSF is well sampled, sharper (bigger telescope), contains a simple pupil, and is on the whole much smoother. The smoothness of the AO PSF is in part due to the atmosphere smoothing the fixed speckle pattern that would otherwise result if there was no atmosphere (as in the case of HST). As figure 1 illustrates the NICMOS PSF is much more complex, which hinders the detection of faint companions, especially since the PSF changes between frames due to HST's thermal "breathing" shifting the focus between frames (Barbieri et al. 1996; Krist 1997; Krist 1998).

With UHAO and Hokupa˙a we have discovered many new faint companions. In particular, we have discovered the 0.7" companion to the famous "Hubble's variable nebula star" R Mon. The fact that R Mon's companion was 250 times fainter and only 0.7" away kept its presence a secret even though thousands of images have been taken of the star throughout the years. The discovery of the companion has allowed us to date the age of R Mon as very young (10^5 yrs of age; Close et al. 1997b)

We have also used UHAO to survey 151 square arc min of the young (100 Myr) open cluster α-Persei (D=150 pc). Capitalizing on the excellent efficiency of the curvature AO system we locked up on 151 guide stars in the α-Persei cluster in 3 days at the UH 2.2m telescope on Mauna Kea in Dec 1996 (Eisloeffel, et al. 1998). We also mapped out the inner 5 square arc min of the Orion Trapezium cluster (10 Myr, D=450 pc) and detected 295 cluster members (Simon, Close, & Beck 1998). By using PSFs from these data sets highly accurate completeness limits could be estimated and the true frequency of binary systems (B.F. = # of binaries/total # of stars) could be calculated. In Figure 4, we plot the completeness limits and all the detected binaries from the 2.2m observations of α-Persei and the Trapezium cluster. As with the Hokupa˙a data, the sensitivity curve matches the data very well. Based on these detections it becomes clear that binary systems are much less common in clusters (B.F.=4±1% for $166<a<332$ AU) compared to isolated dark clouds where the B.F.=13±4% in the same semi-major axis range (value averaged over the Taurus, Oph, Cha, Lup, and Chr A clouds; Ghez et al. 1997). The B.F. in the field of the local galaxy is 4.6% for $166<a<332$ AU (and 4.9% for the Pleiades cluster; Bouvier et al. 1997) which is similar to that of our cluster observations. Since binaries appear rarer in clusters, it is possible to speculate that the formation of companion stars is discouraged in cluster environments (possibly due to the harsh, ionizing, strong, UV flux and winds from the central OB stars in a cluster -which may destroy protoplanetary disks in a short ~10^5 yr). One also gleans that most star systems seem to form in cluster environments (since the cluster B.F. and Field B.F. are observed to be nearly identical). See G. Duchene's paper in these proceedings for detail about the B.F. in young clusters

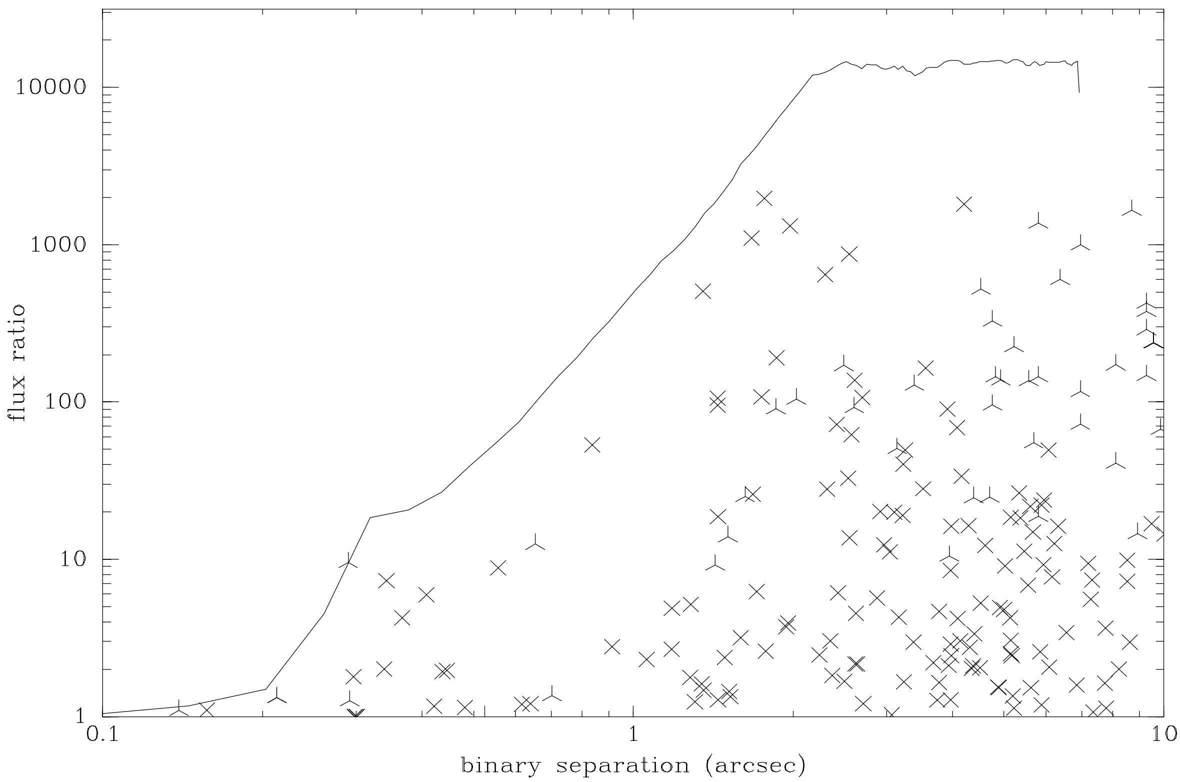

Figure 4: The sensitivity of the old UHAO 13 element system at the UH 2.2m. Note how closely the sensitivity curve (calculated from the observed PSFs) matches the upper limit for binary detection. The data points are from the α-Persei and Trapezium young star clusters. The cut-off in sensitivity at 10000 is due to the 5 min limit of the exposures. The FWHM of the K PSF is 0.24".

Faint companion detection works extremely well with adaptive optics since, companions that could not be measured above the read-noise in short 0.5s speckle observations (max flux ratio~50) are now easily detected. Moreover, AO can even image faint companions through narrow band filters coupled with very long (20 min) exposures that are impossible with speckle or HST observations. For example we have used special narrow-band IR filters to look at the geology of the Pluto Charon binary with deep 20 min exposures (Owen et al. 1998).

3.0 Imaging with resolved guide sources: Solar systems objects, planetary nebulae, protostellar nebulae

A curvature system can naturally guide on resolved objects by reducing its membrane stroke (therefore decreasing the extra-pupil distance on the lenslet array). In this manner Hokupa`a can guide on objects that are 3.0” in diameter. This technique naturally lends itself to solar system objects.

The UHAO team, lead by Francois and Claude Roddier has carried out many solar system observations at diffraction-limited resolutions. Some highlights are imaging of Neptune in narrow band methane filters (Roddier F. et al. 1997a). Detection of Neptune’s dark moon Proteus (Roddier et al. 1997). These 0.1” images of Neptune are very impressive considering that the guide source is Neptune itself (~3.0” across) and it rotates so fast that only a large 4m telescope with AO can easily resolve the fine features of the high altitude clouds in narrow band filters.

Other resolved solar system objects imaged are Uranus and its moon Puck (Roddier F. et al. 1997b), Titan’s surface and atmosphere (Han et al. 1995). During the Saturn ring crossing in August 1995, nine new moons (or ring clumps) were discovered in orbit around Saturn (Roddier F. et al. 1998, 1997c,1996a-b; Roddier C. et al 1997; Ferrari et al. 1997). On June 16, 1997 we used UHAO to image at 0.13” resolutions the K-band light from volcanoes on the surface of Jupiter’s moon Io (Dumas et al. 1998). Similar images have been made of the asteroids Vesta, and Ceres (Dumas et al. 1988). All of these observations are proof that exciting diffraction-limited observations can be made of solar system objects using resolved guide sources. For a complete review of these exciting observations please see F. Roddier’s paper in these proceedings.

Of course, we have made many observations with resolved guide sources of non-solar system objects. Some examples are protoplanetary nebulae: Frosty Leo and the Red rectangle (Roddier et al. 1995), the Saturn Nebula (NGC 7009), the Butterfly Nebula (M2-9), and the Hubble 12 nebula (Hora et al. 1998). In all these cases diffraction-limited images were obtained guiding on extended sources of angular extent from 0.5-3.0” FWHM.

Sometimes in extreme cases it is required to guide with *very* extended objects (>10”) with little point-like structure. In these cases we simply lock up on a nearby SAO star, then freeze the deformable bimorph mirror (DM) in its mean position (to remove all static optical aberrations), then nod back to the science target and simply tip-tilt with the frozen DM. By just rapid centroiding we can partially correct the image (by the removal of image motion) while guiding on very extended, irregular sources. Some examples of systems where this technique has worked are the Egg Nebula, Par 21, V635 Cas, and LkHα 198. In each of these cases final image resolutions of 0.2-0.3” were obtained, with final PSFs that were very smooth since the frozen DM removed all the higher frequency optical aberrations (like the trefoil from the CFHT’s 3 point support print through).

4.0 Off-axis guide stars: galactic center, young star clusters

It is often the case that the desired science target is too faint in the visible to be used as a guide star. If there are no nearby bright stars we freeze the DM and can tip-tilt on the science target itself --down to magnitudes of R=17-18. Guiding on objects this faint usually requires the use of a moon-light blocking iris (at a WFS field stop) stopping down the wavefront sensor FOV from 3” to 1”. This usually yields ~0.3” images from tilt correction with the frozen DM.

However, it often possible to lock up on a much brighter star that is off-axis from the science target. An excellent example of this is the Orion Trapezium cluster work where only 5 individual stars in the cluster were used as guide stars to image 5 square arc min of the cluster containing 290 off-axis stars (Simon, Close & Beck 1998). In this particular case it was found that at K band images were within 0.2” of the diffraction-limit up to 60” from the guide star (at J band the distance is only ~12”). However, occasionally gale force upper atmosphere winds shrink isoplanatic patch to less than 5” at K-band -- although this is quite rare at Mauna Kea. In any case, the dependence of the PSF shape on distance from the guide star is an annoying and difficult problem. We were able in the Trapezium cluster to calibrate the change in PSF across the FOV by use of the DAOPHOT variable PSF fitting algorithm “psf”. Indeed, in a crowded star field (where we know most sources are point-like) this algorithm allows the PSF to change in a quadratic manner as a function of distance from the guide star, this allowed us to preform accurate PSF fitting photometry even in crowded off-axis fields. The procedure worked best in “annuli” of 10” width from the guide star, and were comparable to aperture photometry errors of $\pm .2$ mag. However, even though the change in the PSF was accounted for in the reduction we still loss sensitivity to faint companions at the largest separations from the guide stars.

Off-axis guide stars produce an elongation in the science object’s PSF towards the direction of the guide star (usually about 0.15” of elongation at 12” radial distances in J band at CFHT). As was mentioned above, these isoplanatic patch induced elongations can be at least calibrated in crowed star field observations, hence their impact to the science can be minimized.

A much more difficult problem occurs in the case a faint galaxy near a brighter star for example. If the galaxy is too faint to be guided on, one is forced to use the off-axis star as the guide star. If the star is near the edge of the isoplanatic patch the galaxy will certainly be elongated towards the guide star in a somewhat undetermined manner and amount (assuming no other stars in the field can be used as external calibrators). Depending on the scientific objectives this may result in a poor determination of the galaxy’s morphology. For example, an isoplanatic elongation could be mistaken for the host galaxy of a quasar. Offsetting to a rich star cluster and calibrating the off-axis PSF at the time of the observation, (guiding on a similarly bright star), may be a solution. But since the isoplanatic patch is variable over timescales from minutes to hours, (and the availability of PSF clusters at similar airmasses is rare) such calibrations could be problematic.

It is worth noting that the PSFs generated from the wavefront sensor signals alone would not reconstruct the proper PSF since by definition the guide star is always on-axis to the wavefront sensor. Therefore, scientific cases of a faint object beyond the isoplanatic patch of the guide star should be avoided. We usually avoid this by either tip-tilt correction on the faint science object itself, or by increasing the wavelength of the observation to enclose the science target inside the isoplanatic patch.

CONCLUSIONS

It is now clear that natural guide star AO systems are producing unique, exciting, astronomical observations on a regular, reliable basis. Here we have only outlined four applications of AO, nevertheless in these four situations (extended light around a point source, faint companions, resolved guide sources, and cluster imaging) a wealth of new scientific results has resulted from our program already. Extrapolating from the increase in scientific papers produced with our system alone, suggests the future for natural guide star science looks very bright. However, a cautionary note is that PSF determination is crucial to obtaining meaningful scientific results from any AO system. Any situation where the PSF is not stable, smooth, symmetric, and of moderate strehl should be avoided. In particular, off-axis imaging outside (or even near) the isoplanatic patch should be avoided if the PSF cannot be calibrated.

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