HIGH CONTRAST IMAGING WITH ADAPTIVE OPTICS

Laird Close

Steward Observatory
University of Arizona

1.0 Optimizing an AO system

From Don Gavel's talk we learned that:

Since:

Strehl Ratio =SR ~ exp(-($\mathrm{sigma}_{aniso}^2 + \mathrm{sigma}_t^2 + \mathrm{sigma}_{rec}^2 + \mathrm{sigma}_{fit}^2$))

Which can be written:

SR ~ exp(-(($\mathrm{theta}/\mathrm{theta}_o$)$^{5/3}$ + ($\mathrm{deltaT}/\mathrm{tau}_o$)$^{5/3}$ +

$(13/N)(1+4n^2/N)(\text{lambda}_{WFS}/\text{lambda})^2 + 0.54(D/r_o)^{5/3}(Ns)^{-5/6}$)))

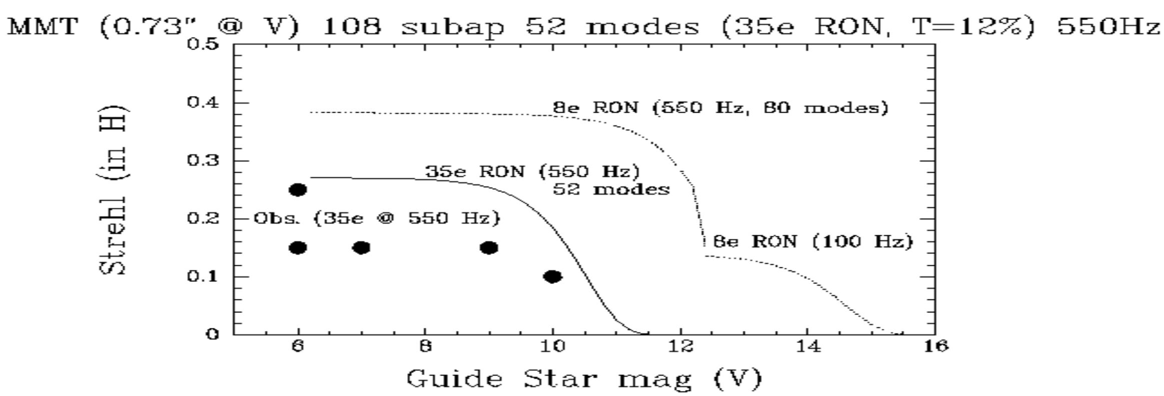
There are two important cases to look at in detail: bright and faint guide stars.

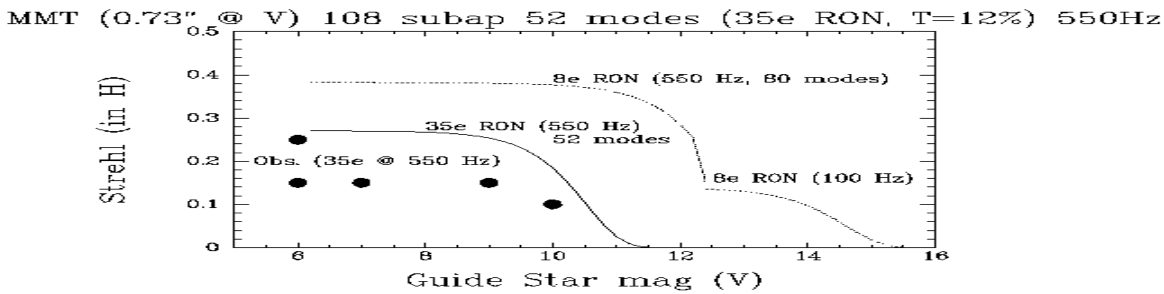
In the case of faint guide stars the dominate error is sigma_reconstructor so you really need a low (n) readnoise WFS

In the case of ExAO (Extreme AO) we have typically a bright central guide star, then sigma_fit or sigma_tau can dominate so we need a fast (small deltaT) and high order (Ns) AO system.

Conclusions:

An AO system optimized for bright guide stars (ExAO) is very different from one optimized for faint guide stars.





Above we have a real example of how the performance of an AO system is effected by the brightness of the guide star (V=5-16 mag), the readnoise (n=8 or 35 e rms), the number of modes corrected (Ns=52 or 80), the integration time (deltaT=0.0036 or 0.01 seconds). This is initial engineering data from the last MMT AO run. The observed SRs are close to that expected from theory, but are somewhat lower due to 0.02 arcsec rms vibrations in the MMT at ~18 and ~38 Hz.

2.0 Imaging gains with Adaptive Optics

An AO enabled telescope has many advantages:

2.1 Imaging point sources (unresolved objects)

In AO images of point sources (objects that appear unresolved ---like single stars) the flux is is contained within a diffraction-limited core of FWHM= 0.98*lambda/D

So as the size of our telescope diameter (D) increases:

1) we collect photons over a telescope_area = pi*$(D/2)^2$ m^2 area

2) and we place those photons in a area of PSF_size = pi*$(0.98*\text{lambda}/D)^2$ arcsec^2

3) the normalized peak counts of the central PSF pixel scales as the PSF_size (if SR is constant)

therefore we see that number of photons we have falling onto our central (say 0.020x0.020 arcsec) pixel of our detector will scale as:

#of peak photons/s = (flux of source) * (telescope collecting area) * (normalized peak counts) * (size of the central pixel)

therefore the flux for a point source can be expressed as:

# of peak photons/s varies as pi*$(D/2)^2$*pi*$(0.98*\text{lambda}/D)^2$ or as D^4

So an AO equipped 3.0 m telescope will take 16 times longer to collect the same number of peak photons from a faint point source than an AO equipped 6.0m telescope would (assuming the same SR)

Often the SR falls for the larger telescope. A more general expression for 2 telescopes of sizes 1 and 2:

ratio of speeds$(D_1/D_2) = (D_1/D_2)^4 * (SR_1/SR_2)$ assuming that both telescopes have the same size pixels (in arcsec on the sky)

example: Say D_2 = 3.0 m and D_1 = 6.5 m; typically SR_2 ~ 60% at 2.2 um and typically SR_1~40% at 2.2 at the larger scope (due to poorer fitting error which is typical for a larger scope).

Then we see the 6.5m (even with just 40% strehl) is still 15 times faster than a 3 m scope with 60% strehl.

It is also worth noting that in the case there is no AO on the 3 m then SR_2~0.5% at 2.2 um. In that case the 6.5m is 1800 times faster than a 3 m without AO (assuming as above that both scopes use a 0.02" pixel). Hence we see that most NIR imaging of faint point sources is best done with AO or HST currently (especially in cases where a large field of view is not required).

2.2 Imaging resolved objects

In the case of resolved objects the advantages to AO are less clear.

If the object being imaged has *NO structure* at or near the diffraction-limit (of the telescope) then there is no improvement in the image as the PSF becomes sharper. This makes sense of course, and in these situations AO correction is of little use.

example: a 2" (arcsec) sized perfectly smooth "galaxy" will be detected equally fast with or without AO.

However, almost all objects, in fact, do have "sub-structure" that is unresolved and therefore benefits from AO correction. As well, in case of circumstellar disks, there is a large contrast advantage to "sweeping" up PSF halo light into a diffraction-limited core -- to reveal the faint circumstellar disk.

SCIENCE TIP: So if there are point sources (or substructure) of scientific interest than it is usually advantageous to use AO if possible. The bigger the telescope the better!

3.0 At what wavelengths is Astronomical Science currently done with AO?

As the table below shows most AO science is done between 1-2.5 um currently. (note wavelengths of "mm" in table 1 should read as microns)

Table 1: Summary of the Utilized Science Techniques by number of papers published

Science Wavelength	Broad Band	Narrow band	Polari-metry	Corono-graphy	2D spectra	IFU spectra	TOTAL
Visible 0.5-1.0 mm	8 papers (2 new) 5.5%	3 (1 new) 2.1%	difficult no papers	soon to be pub-lished	soon to be pub-lished	1 paper 0.7 %	**8.3%**
Near IR 1.0-2.5 mm	**97 (39 new) 67.4%**	13 (8 new) 9.0%	4 (1 new) 2.7%	5 (2 new) 3.5%	3 (3 new) 2.0%	3 (3 new) 2.0%	**86.6%**
Thermal IR 3.1-4.1 mm "L Band"	5 (1 new) 3.5%	soon to be pub-lished	difficult	not likely planned	difficult	not planned	**3.5%**
Thermal IR 4.6-5.0 mm "M band"	2 (2 new) 1.4%	difficult	not planned	not likely planned	difficult	not planned	**1.4%**

The reason 86.6% of the papers have been focused on science from 1-2.5 microns is for the following reasons:

1) Fitting error drives ExAO to the NIR since the visible is too hard:
is given by $sigma_{fit}^2 = 0.54(D/r_o)^{5/3}(Ns)^{-5/6}$ then in the case of bright guide stars:

therefore we need:

$Ns > (0.54/sigma_{fit}^2)^{6/5}(D/r_o)^2$ actuators needed (8)

Now if we wish a reasonable maximum SR of 74% (a minimum for good ExAO) then we must keep $sigma_{fit}^2$ to less than 0.3 rad^2

Example: In the case of using the K band (2.2 microns) and a D=6.5m telescope (at a good site $r_o(2.2)$=79cm) so (from equation 8):

Ns = 137 actuators at K band (2.2 microns)

Now in the case of visible light r_o is much smaller ($r_o(0.55)$=15 cm at a good site) so:

Ns = 3801 actuators at V band (0.55 microns)

Clearly it is much easier to build a 137 element system than a 3801 actuator system! Hence, most AO systems are designed to only deliver decent SR for lambda > 1.0 micron.

An exception to this is the 1000 element system located in Maui. This system was built by the Military (Air Force) for imaging low earth orbiting objects. Since many satellites are bright they do not mind having a limiting magnitude of V~7 th for their guide star, since it allows them to work in the visible.

SCIENCE TIP: Strehl Ratios in the visible are very small due to fitting error at almost all telescopes.

2) Thermal background makes ExAO in the MIR less sensitive:
Indeed from equation 8 one would be tempted to use as long a wavelength (lambda) as possible to maximize the ro (and therefore maximizing the SR). However, there are 2 problems with going to wavelengths longer than 2.5 microns:

a) the resolution of the images decreases as (in arcsec; where D is in microns) FWHM~0.98(lambda/D)*206264, (NB: without AO it is fixed at $FWHM_{seeing}$~(lambda/r_o)*206264) so bigger lambda, lower resolution....

b) the sky, telescope, and warm optics start to "glow" at wavelengths longer than 2.2 microns...

Table 3: The Effect of Wavelength on Sky and Thermal Background Photons

(assumming Nyquist sampled λ/2D pixels)	J 1.26 µm	H 1.62 µm	K' 2.21 µm	L 3.50 µm	M 4.85 µm
sky+scope background in detected photons/s/pix for Nyquist sampled IR Camera (total QE=35%)	9.7	121	161	603,374	22,827,986
AO system extra emissivity ε=25% @ T_{AO}=300K (detected ph/s/pix)	0.01	0.6	229	1,020,456	47,846,792
Total background ph/s/pix	9.7	121	390	1,623,830	70,674,778
Strehl at an 8m scope with moderate/high order AO system	0.30	0.50	0.70	0.86	0.93
Resolution (arcsec) 8m scope with the above strehls	0.031	0.041	0.057	0.091	0.126

Table 3: The Effect of Wavelength on Sky and Thermal Background Photons

(assumming Nyquist sampled λ/2D pixels)	J 1.26 μm	H 1.62 μm	K' 2.21 μm	L 3.50 μm	M 4.85 μm
sky+scope background in detected photons/s/pix for Nyquist sampled IR Camera (total QE=35%)	9.7	121	161	603,374	22,827,986
AO system extra emissivity ε=25% @ T_{AO}=300K (detected ph/s/pix)	0.01	0.6	229	1,020,456	47,846,792
Total background ph/s/pix	9.7	121	390	1,623,830	70,674,778
Strehl at an 8m scope with moderate/high order AO system	0.30	0.50	0.70	0.86	0.93
Resolution (arcsec) 8m scope with the above strehls	0.031	0.041	0.057	0.091	0.126

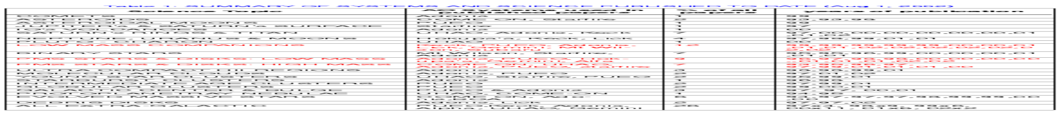
It becomes pretty clear from table 3 (above) why there have been very few papers published at L (and none at M band). The reason is there simply too much noise in each image from the thermal background. Indeed, going from K' to L band increases the noise of the image by 64 times, requiring 4163 times more integration time to reach the same detection level on a flat-spectrum source.

However, there are some very cool targets of great scientific interest (like the cool T~300 K dust disks around nearby stars, or mature giant gas planets), so if we wish to image these objects it might in fact be best to work at M (4.5) or N (10 microns). The best system for this would be an adaptive secondary like that built for the MMT.

4.0 A survey of the literature

Table 1: SUMMARY OF SYSTEMS AND SCIENCE PUBLISHED TO DATE (Aug 1, 2002)

Science Topic	AO Systems used in published papers	% of all papers	years of publication
COMETS	Adonis	1	99
ASTEROIDS	COME ON, Starfire	2	93,93,98
ASTEROIDAL MOONS	PUEO	1	99
JUPITER's & SATURN's SURFACE	Starfire	1	97
IO's VOLCANOES	Adonis	1	00
SATURN's RINGS & TITAN	UHAO, Adonis, Keck	7	97,00,00,00,00,00,00,01 ,01,02
NEPTUNE, URANUS & MOONS	Hokupa'a, Keck, Lick	4	97,98,99,01,01
PLUTO - CHARON	UHAO	1	00
LOW MASS COMPANIONS	Keck, PUEO, Adonis, Lick, Gemini, Mt Wil- son, Subaru	12	99,99,99,99,99,00,00,01 ,01,01,02,02,02,02,02,0 2,02
BINARY STARS	Mt Wilson, Starfire, Adonis	7	95,95,96,99,00,00,00,01 ,01,01
PMS STARS & DISKS: LOW MASS	Adonis, PUEO, Hok- upa'a, Gemini, Alfa	9	96,97,98,98,00,00,00,00 ,,01,01,01,02,02
PMS STARS & DISKS: HIGH MASS	COME ON, UHAO, Adonis, PUEO, starfire	7	93,95,96,97, 97,99,01,01,01,00
ULTRA COMPACT HII REGIONS	Adonis	3	98,98,99,01
MOLECULAR CLOUDS	Adonis, PUEO	2	97,01,02
YOUNG STAR CLUSTERS	UHAO, Starfire, PUEO	2	95,99,01
STARBURST CLUSTERS	Adonis	1	96,98
INTERMEDIATE AGE CLUSTERS	PUEO	2	97,99,01
GLOBULAR CLUSTERS	PUEO	2	99,00,01
GALACTIC CENTER & BULGE	PUEO & Adonis	3	97, 97, 00,01
PROTOPLANETRAY NEBULAE	UHAO, COME-ON	1	94,95
EVOLVED MASSIVE STARS	COME ON, Ado- nis,BOA	6	94,97,97,97,98,99,99,00 ,00
DEBRIS DISKS	Adonis, Lick	2	97,97,02
ALL EXTRA-GALACTIC	PUEO,Keck, Adonis, Alpha, UHAO, Gemini	26	97x4, 98x9, 99x6, 00x11, 01x6, 02x2

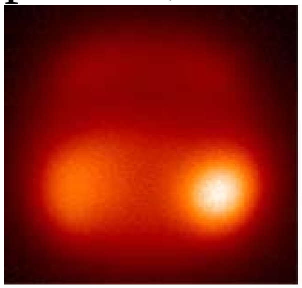
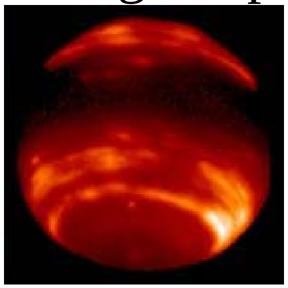


Popular ExAO topics include:
1) looking for faint, cool low mass companions to stars (like extra-solar planets, brown dwarfs etc.)
2) looking for circumstellar material around young (and mature) stars (like disks, shells, etc.)
3) looking at binary stars to understand orbits, masses, etc.
4) looking at morphology of bodies in the solar system
5) looking at the morphology of galaxies and quasar hosts

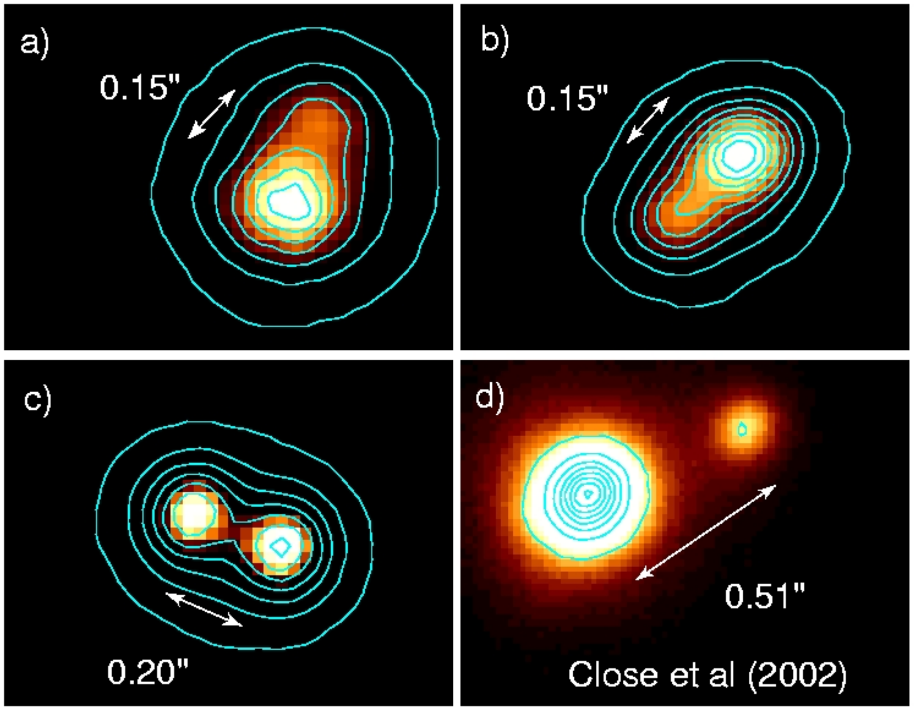
5.0 THE FUTURE

Some fields where the AO systems will continue to do interesting science are:

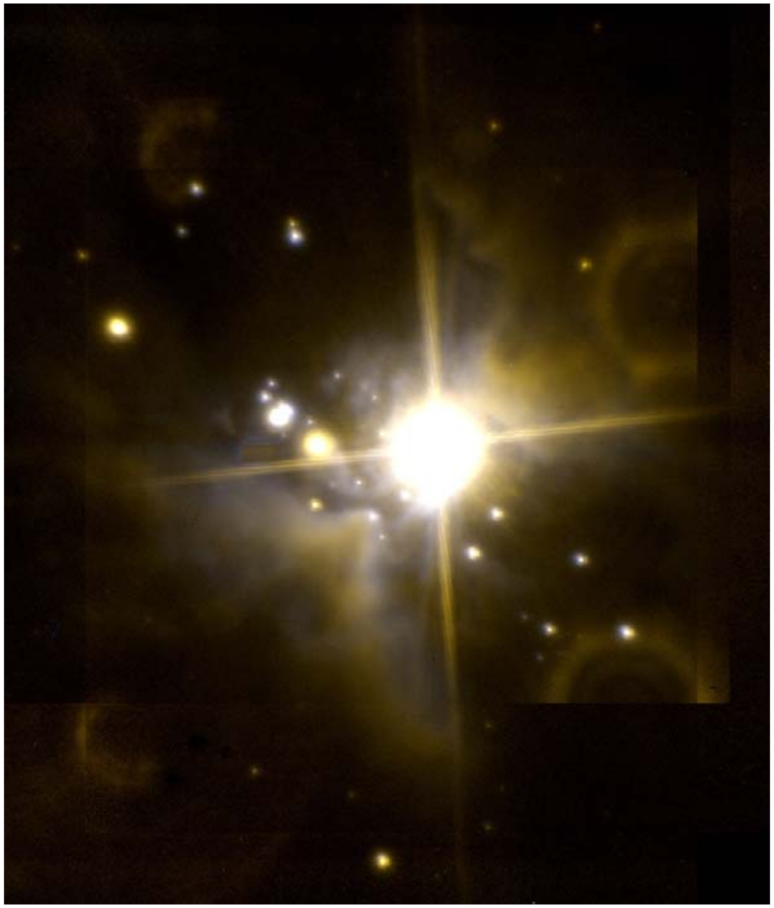
1) Planetary science: -asteroidal surfaces, asteroidal Moons, Moons of Giant planets, clouds of giant planets etc.

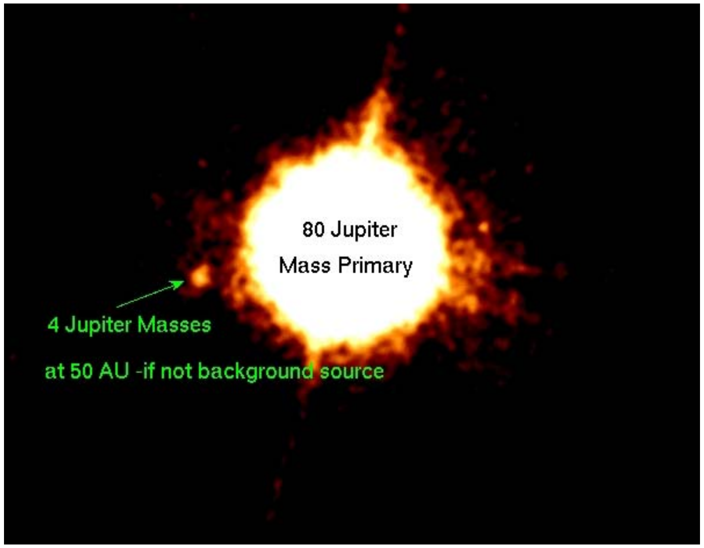
2) Stellar astronomy: -young binary stars, stellar clusters, crowded field work etc.



3) Star Formation: -young binaries, circumstellar disks, embedded clusters, nebulae etc.

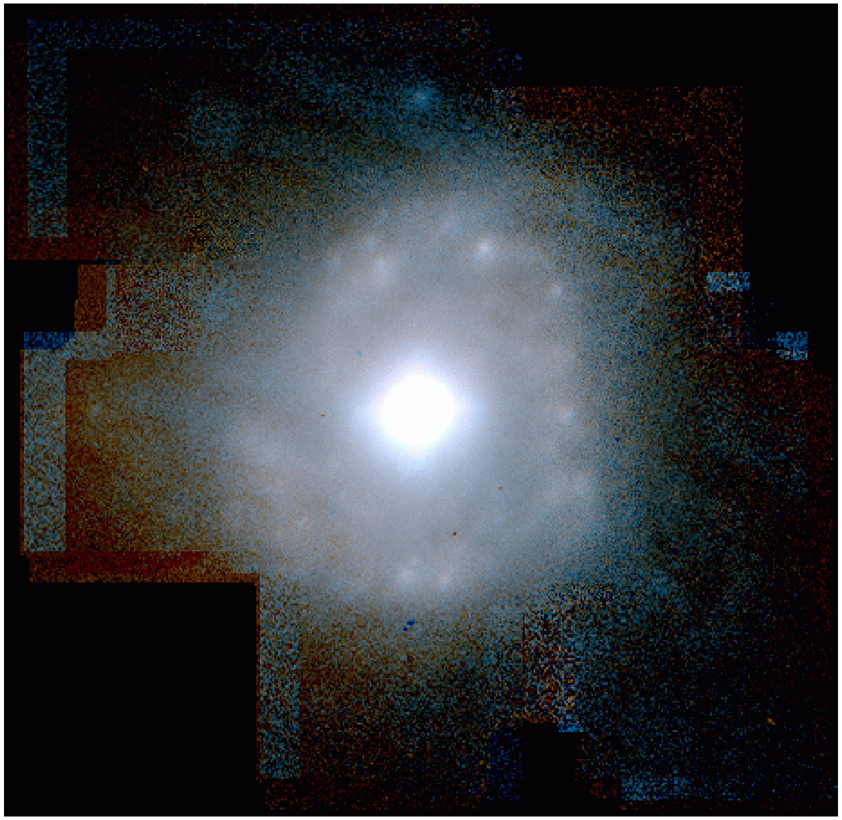


4) Faint companions: -detection of very faint companions to nearby stars, brown dwarf companions, white dwarf companions etc.



link here for a comparison between a 300 element shack hartmann (on the 10m Keck telescope) and a 36 element curvature AO system (on the Gemini 8 telescope). It is clear that in general higher strehls are better for detecting companions at ~0.5" or greater distances -- but inside 0.5" even high strehl images become difficult to probe for faint companions. see later in this lecture for more details.

5) Extragalactic:-detection of host galaxies, companion galaxies, morphology, gravitational lens, interacting galaxies, the cores of nearby galaxies etc.



A picture of NGC7469 from the Keck AO system for more details link here

5.1 PREDICTIONS FOR THE NEAR FUTURE

AO will quickly become the dominant observational technique for the following problems in solar system and galactic astronomy:

A. 60 mas near-IR imaging/spectra of high contrast objects:

Example: Asteroid surfaces, satellite surfaces, equal magnitude binaries, PAH structure...

B. Very faint point source imaging/coronography/spectra near bright point sources:

Example: Low mass companions, young exo-planets/brown dwarfs, asteroidal moons, planetary moons, extra galactic globular clusters, interacting galaxies...

C. Imaging/spectra of surfaces that change quickly with time:

Example: all bodies in the solar system that are resolved, evolved stars, stellar surfaces, gravitational lenses...

D. Imaging/polarimetry/coronography of faint extended structure near bright point sources

Example: Circumstellar disks, debris disks, Ultra compact HII regions, PPNE, Jets/outflows, QSO host galaxies...

E. Imaging/spectra of very crowded star fields/binaries that may be dusty:

Example: Star formation clusters, Globulars, Galactic Center, starbust clusters, Giant HII regions, looking for AGB tip stars and Horizontal Branch stars in distant galaxies...

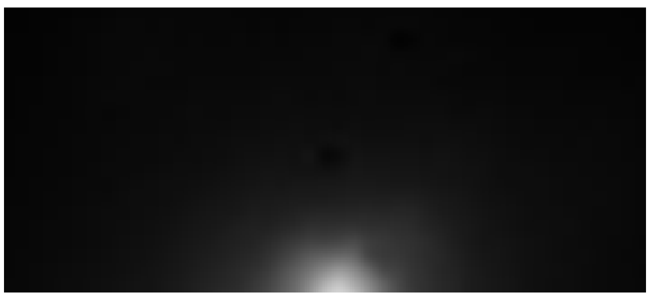
6.0 Artifacts of ExAO imaging

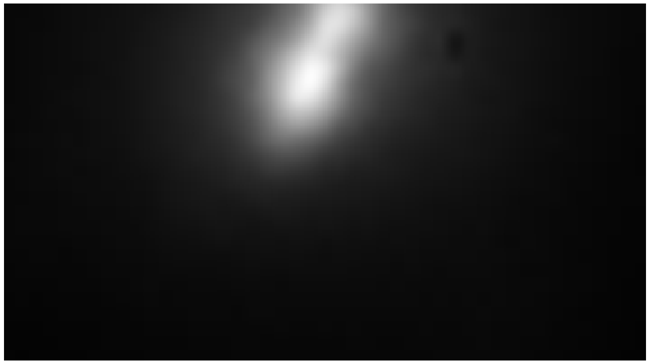
Although imaging with ExAO is very powerful there are some tricks to calibrating the PSF

6.1 Calibrating the PSF

It can often be ambiguous what structure is real and what structure is due to the PSF (the image of a point source).

example: In the movie below (hit the "refresh button" to run this movie) we show a series of images of a tight 0.1" binary asteroid. Although it is clear that there are 2 point sources in orbit around each other, each of the individual images have aberrations that distort each image as it is displayed. But it also shows that the PSF is the same for both objects in the field.



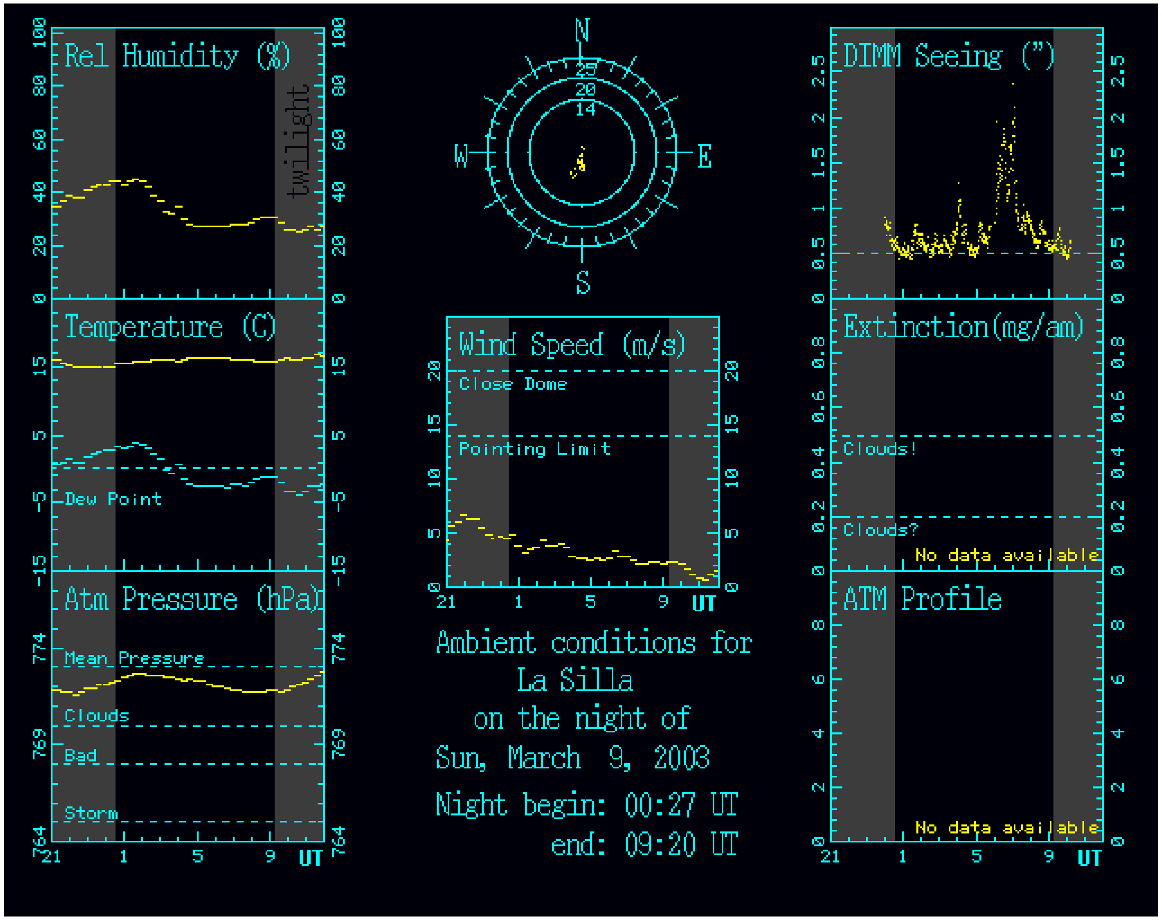


It is clear that there is structure in the PSF that changes image to image.

The reason for this temporal behavior of the PSF is that r_o is changing, the AO correction is changing, and the optical aberrations may also be changing.

Indeed r_o may be changing very fast. Typically r_o can change by 2x in periods of less than 5 min.

here is some typical seeing data from the VLT differential seeing monitor at La Sille Chile from last night:



So it is clear that since the PSF is constantly changing it is best to calibrate it. Since often the amount of science we can extract from our AO images is directly related to the degree we can calibrate (and remove) the AO system's PSF artifacts.

6.1.1. Techniques of PSF calibration

1) The most popular approach to calibrating the PSF is to observe a nearby

guide star at similar location on the sky, with similar colors and brightness. It is important to observe this PSF star as often as possible (before and after the science target). As well it helps to integrate on the PSF star for the same amount of time as the as the science target was observed.

This can work quite well calibrating the PSF to ~5-10 % accuracy. Often this is all that is required. However, there are cases when the science goals require even better accuracy

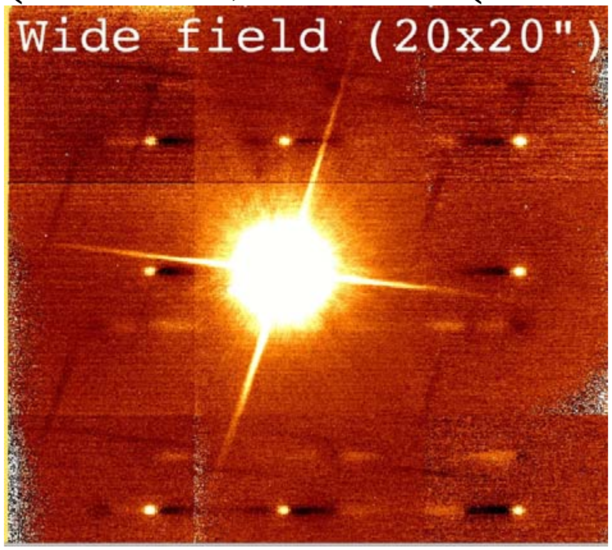
6.2 Detection of very high-contrast (extreme AO).

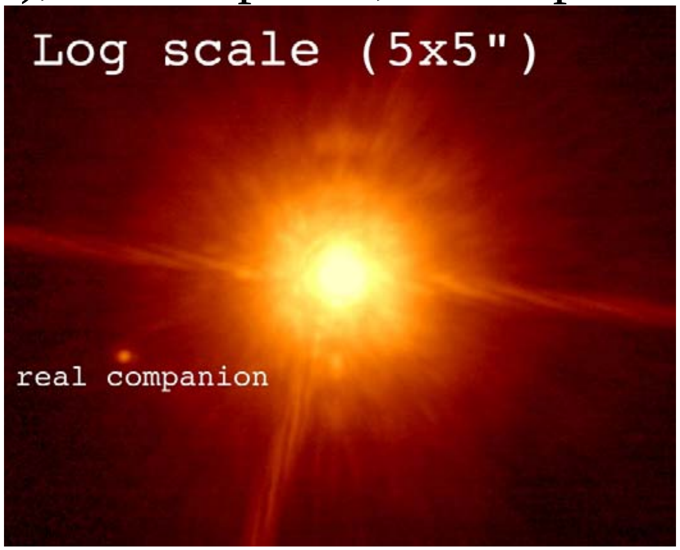
Unfortunately the inner 1.0" of an image is very complex. Each small (~10 nm) sized optical aberration that constructively interferes light in the pupil will produce a very faint "ghost" of the bright guide star. These ghosts are often called "speckles". These speckles are very faint, and due to their chromatic nature, will become very extended at separations greater than ~1.0" from the guide star. Hence speckles can often be ignored for separations greater than ~1.0" from a guide star on an 6-10m telescope (see the Keck image above).

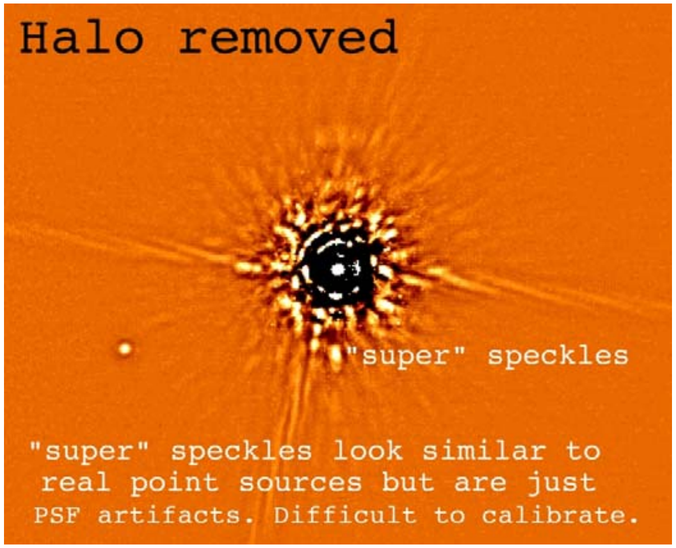
However, if one is interested in detecting very faint objects within 1.0" then it is best to understand the limits placed by "speckle-noise"

Speckle-noise is the noise limit that dominates how close one can image an object next to a guide star. The problem is that the optical aberrations that create "super-speckles" in AO images do NOT disappear and average out over time like speckles produced by the atmospheric aberrations. But once one tries to image a similar PSF star (on a different part of the sky) the flexure of the telescope has changed and the pattern of "super-speckles" is now different (and hence uncalibrated).

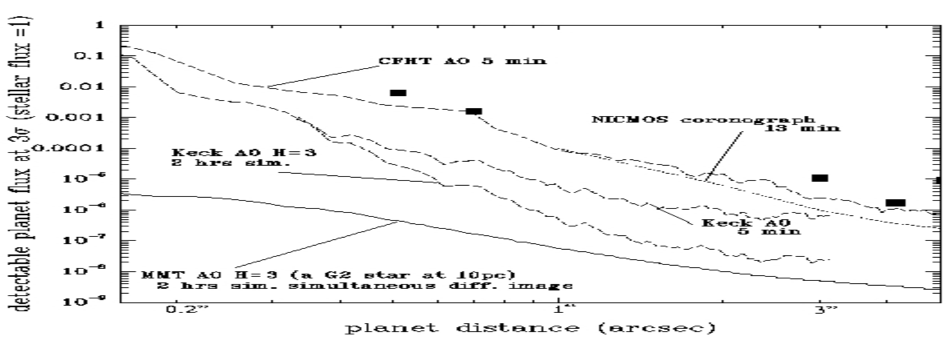
See below for example of "super-speckles" in AO images of bright guide stars (SR~60%, Ks filter (2.1um), 0.013"/pixels, 60s exposure)

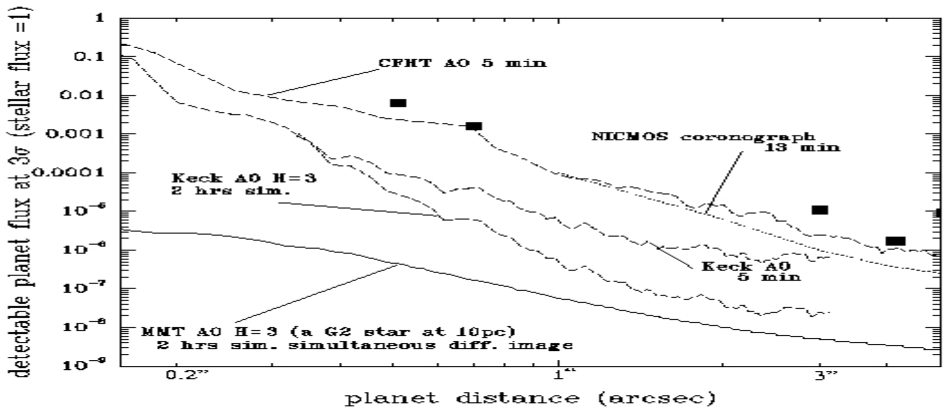




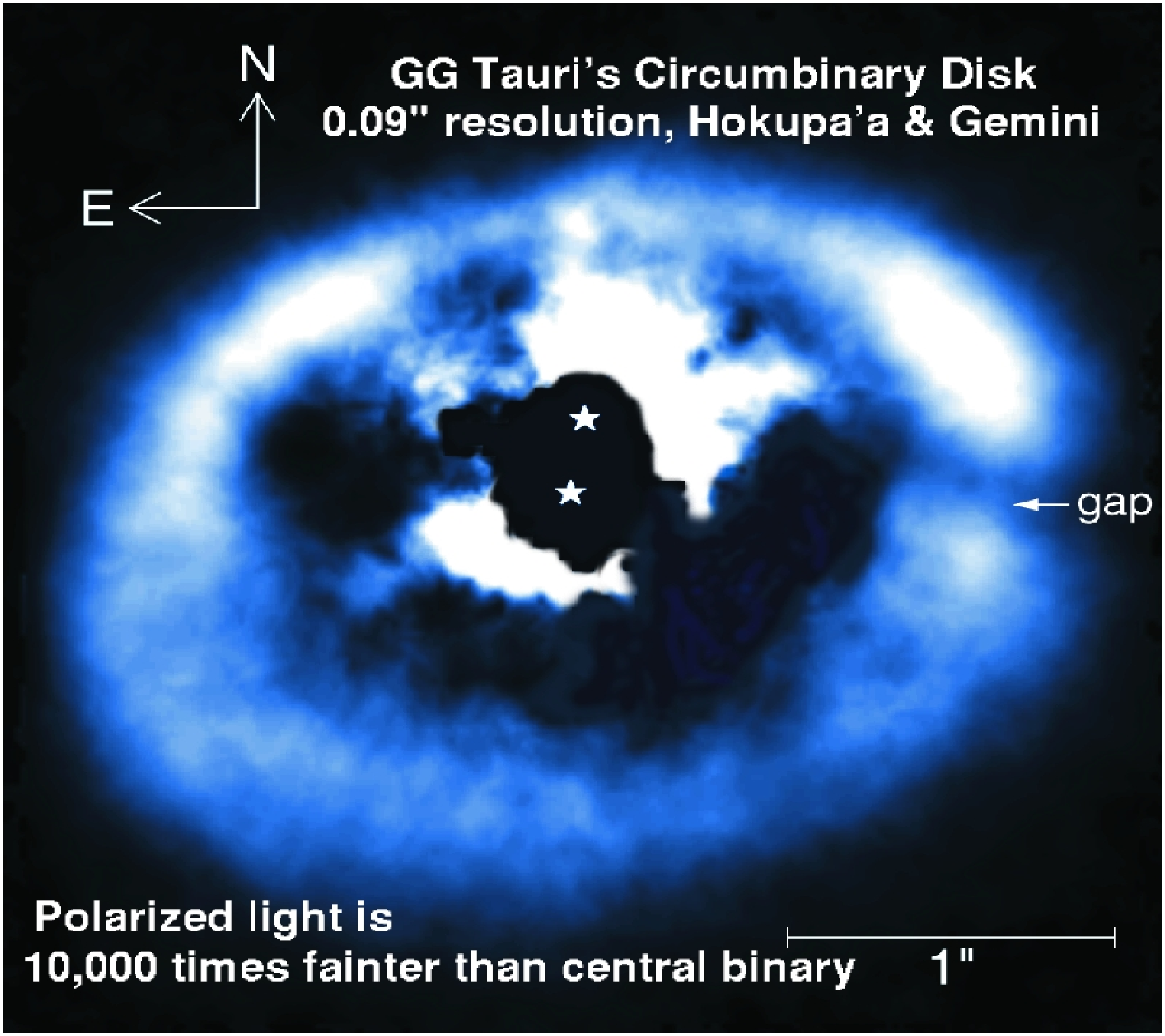


Above we see how a real companion is easy to detect at a separation of 1.7" with the 8m VLT NACO AO system. However inside 1.0" it becomes much more difficult to detect any faint companions because of the "speckle-noise" floor. The far right hand image shows what an AO PSF looks like for objects 10,000 times fainter (like the real companion). It is hard to detect objects 10,000 times fainter within 0.5" of the guide star.





The bottom curve on the above plot is the theoretical "photon-noise-limited" performance of an AO system. This bottom curve ignores speckle-noise. However, in practice we find speckle noise limits the sensitivity of faint companion detection by >200x for separations <0.5". We also see that since the "super-speckles" are from semi-static optical aberrations, they do not average out over time. At separations of <0.4" a 6 minute image and a 2 hour image are equally sensitive (Close 2000). The only way to go deeper in the inner 0.5" is to use special optical "tricks" like nulling interferometry (the next lecture) or simultaneous differential imaging if there is a sharp spectral feature to exploit (like methane absorption in giant gas planets). Calcite Wollastons are one way of simultaneously making 2 images at once.



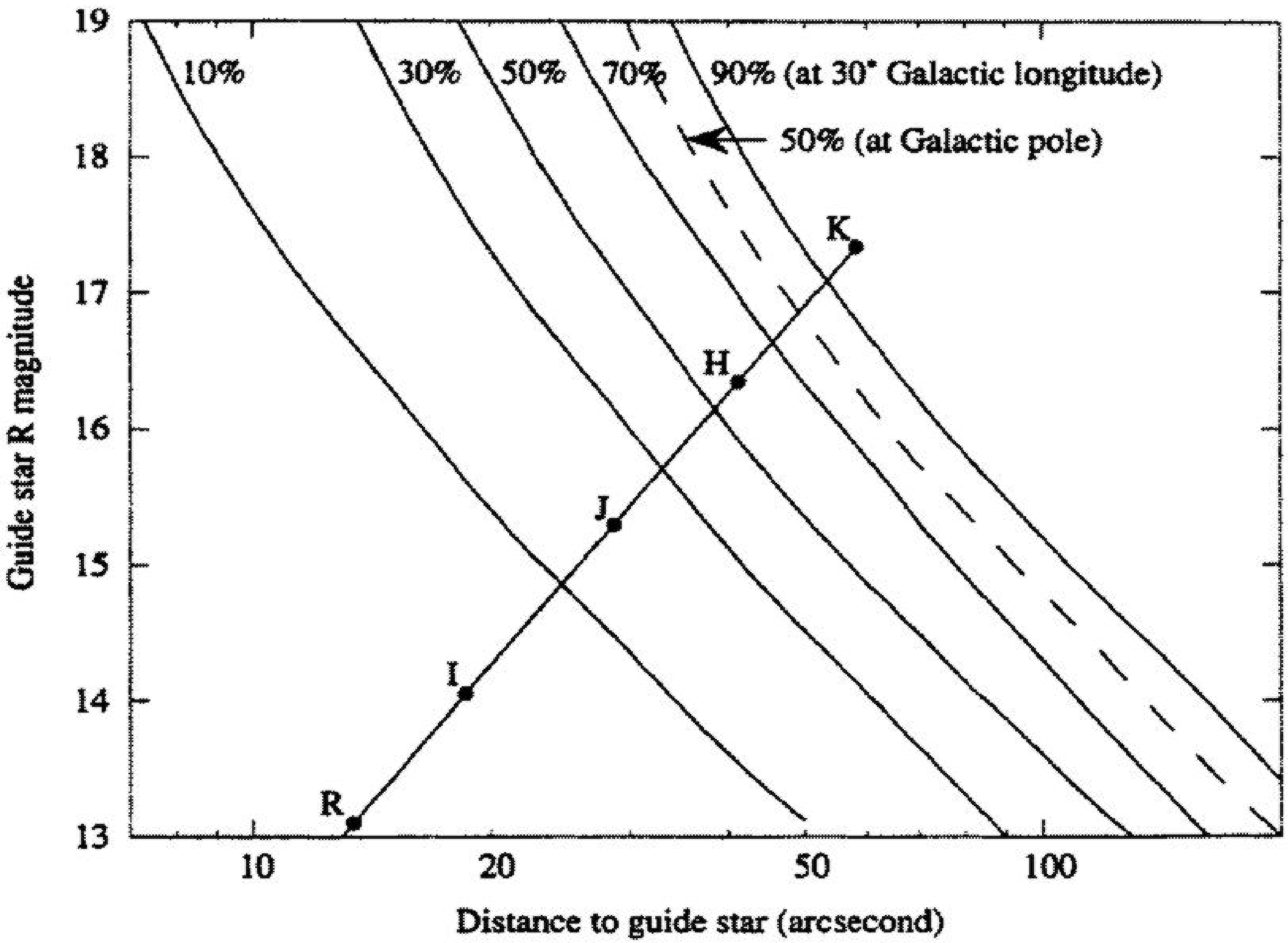
This image of the dust around GG Tau was made by use of a Calcite Wollaston. The wollaston produced simultaneously 2 identical PSFs with opposite polarization. The difference of the 2 beams removes the unpolaized light from the central stars to reveal the much fainter scattered (polarized) light from the dust around the binary (image from Potter et al. 2003)

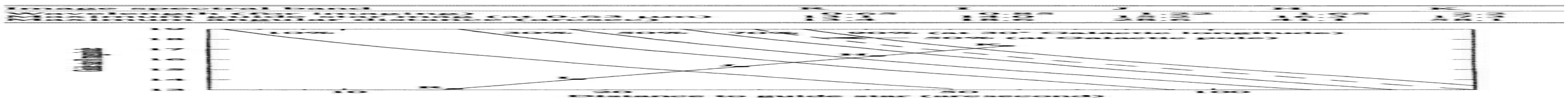
7.0 SKY COVERAGE

A big drawback to AO correction over the whole sky is that you need to have $N>n^2$ to have a low reconstructor error (lecture 6). But we also have to have enough subapertures ($Ns \sim (D/r_o)^2$) to keep the fitting error small. Therefore, there is typically a "limiting-magnitude" (or maximum magnitude) beyond which there is more than a rad^2 of wavefront error. This is independent of telescope size (it just depends on r_o).

In Francois Roddier's book (*Adaptive Optics in Astronomy* - which I highly recommend) he has calculated theoretical "maximum magnitudes" (see table below, Roddier's fig 3.10). So the theoretically faintest guide stars possible are around R~17 if you want a SR~30% at K (2.2 um). Note how quickly this rises to a R~13.1 (a $10^{((17.3-13.1)/2.5)} = 47$ times brighter guide star) if we need a SR of 30% in the R band (0.65 um). In other words, since $r_o \sim \text{lambda}^{6/5}$ you can get the same Strehl on a star 47 times fainter at 2.2 microns compared to 0.65 microns with AO.

Image spectral band	R	I	J	H	K
Wavelength (for imaging)	0.65	0.85	1.22	1.65	2.2
Maximum guide star mag (at 0.63 μm)	13.1	14.0	15.2	16.3	17.3
Maximum angular distance (arcsec)	13.4	18.6	28.6	41.1	58.1





There are far more faint stars in the sky than bright ones. The above graph shows your "chance" of finding a field star at a certain distance from any point on the sky as a function of the brightness of the field star.

For example we see there is about a 10% chance of finding a R=15 mag guide star within 20" of our target (at 30^o galactic latitude), this increases to 50% within 60".

So the fainter the guide star needed the more likely you are to find one close by.

How close do the stars need to be at K?

If we are willing to have $sigma_{aniso}$ = 1 rad^2 then theta can be as large as $theta_o$. In this case the above plot shows that if $theta_o$ is ~60" at 2.2 microns then we can see that there is a ~90% chance of finding a R=17.3 mag guide star in this large area of sky. So (as is noted in the figure by the "dot" at K) it is possible to find nearby guide stars in the K band for good sky coverage at 30^o galactic latitude.

How about the visible (R band)?

In the R band we see $theta_o$ is a much smaller 13.4" (since r_o is so much smaller) and the limiting magnitude is a much brighter 13.1 mag (since N is smaller -> since Ns is larger -> since $(D/r_o)^2$ is larger). So in the R band we need to find

R=13.1 stars within 13.4" of our target! Since R=13.1 is fairly bright (hence quite rare), we see the sky coverage is much less than 10% at R band. This is quite different from the >90% at K band!

Conclusion: There is almost no sky coverage for AO at visible wavelengths, but for low Strehls much of the sky can be used at K band.

In theory the best way of increasing sky coverage is to use laser guide stars... but that is another lecture...

8.0 AO and Coronagraphs

Initially stellar cornographs were used in the visible and with seeing-limited resolutions

SUPPORTING ONLINE MATERIAL
Materials and Methods

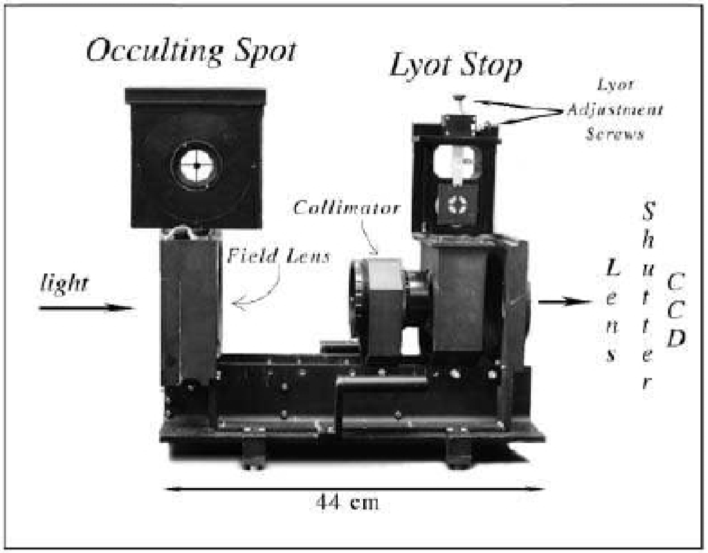
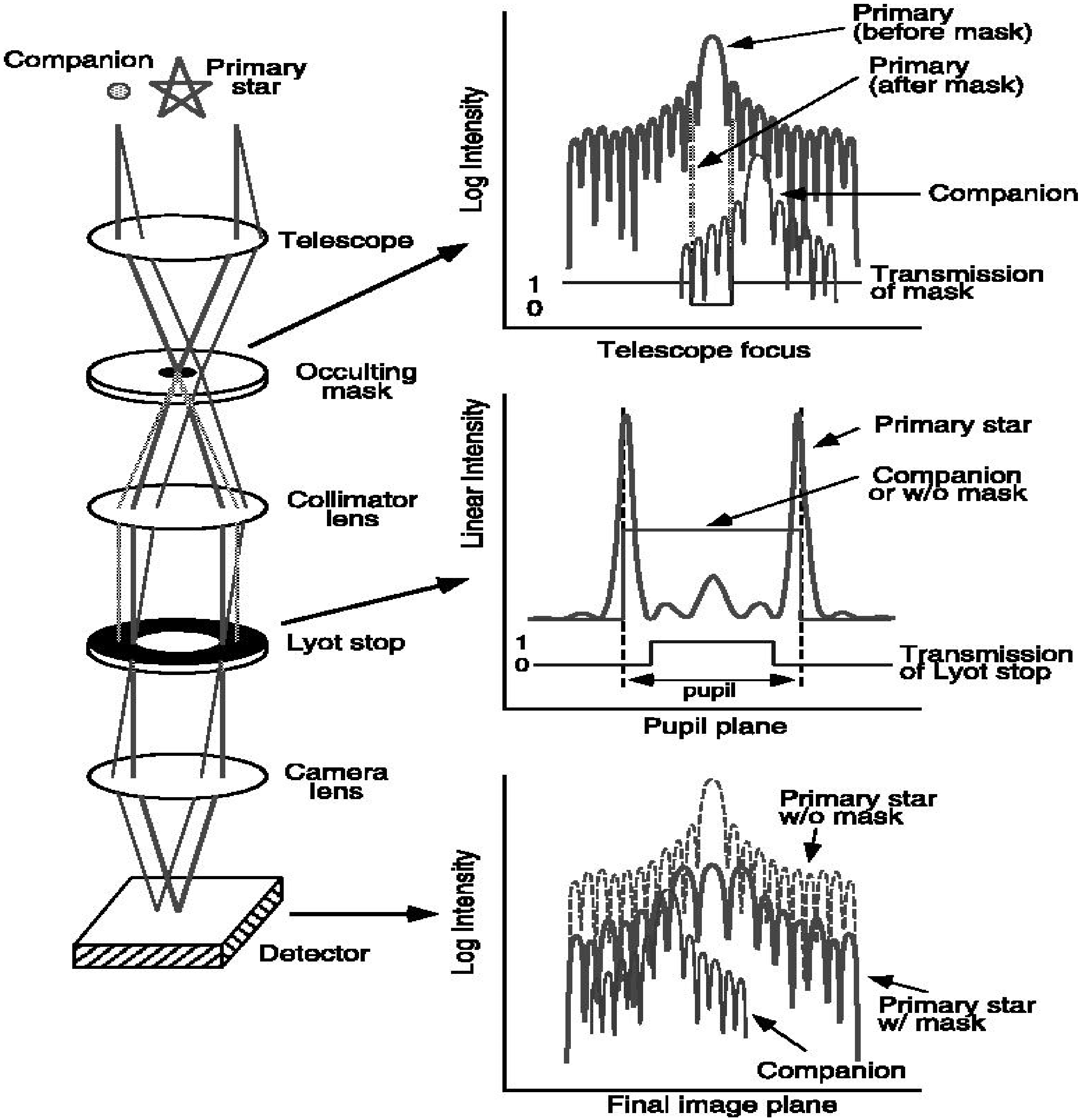
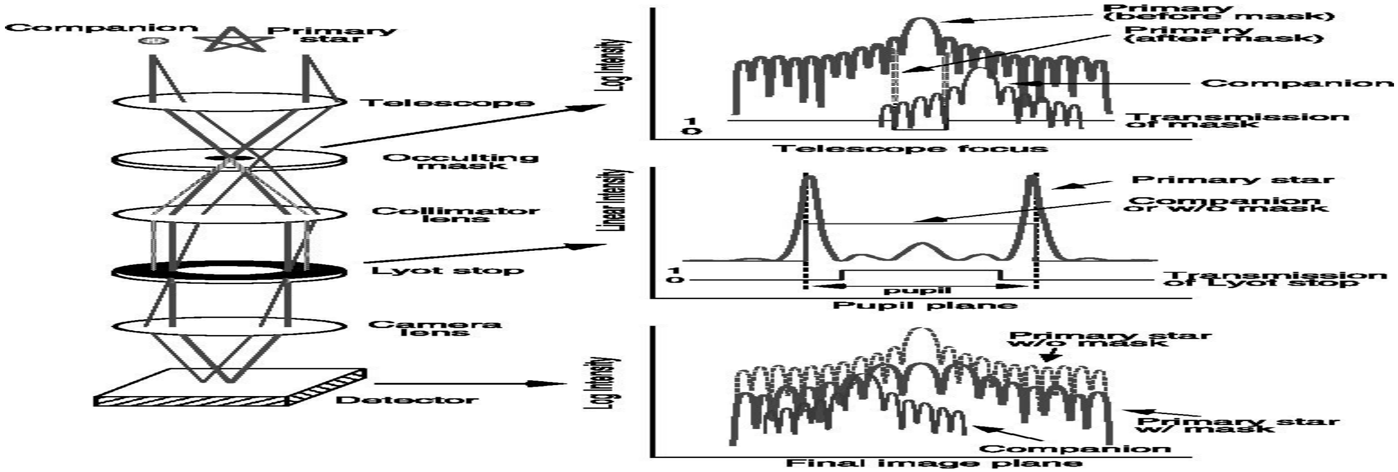


Fig. S1: The optical stellar coronagraph used for these observations. The main function of a stellar coronagraph is to block light from a bright star in order to detect faint, nearby objects. The occulting spot is placed at the focal plane of the telescope and prevents light from striking any optical elements further down in the optical path. Without the occulting spot, light from the star would saturate the CCD, and the optical elements would fill the background with scattered light, as well as produce spurious reflections. The optical elements in the coronagraph are used to create an image of the pupil plane, essentially an image of the telescope mirrors, and support structures. The Lyot stop is appropriately shaped to block this image of the telescope diffraction pattern - stars imaged with a coronagraph do not have diffraction spikes. The removal of the diffraction pattern is a major advantage when trying to image faint sources near the star.

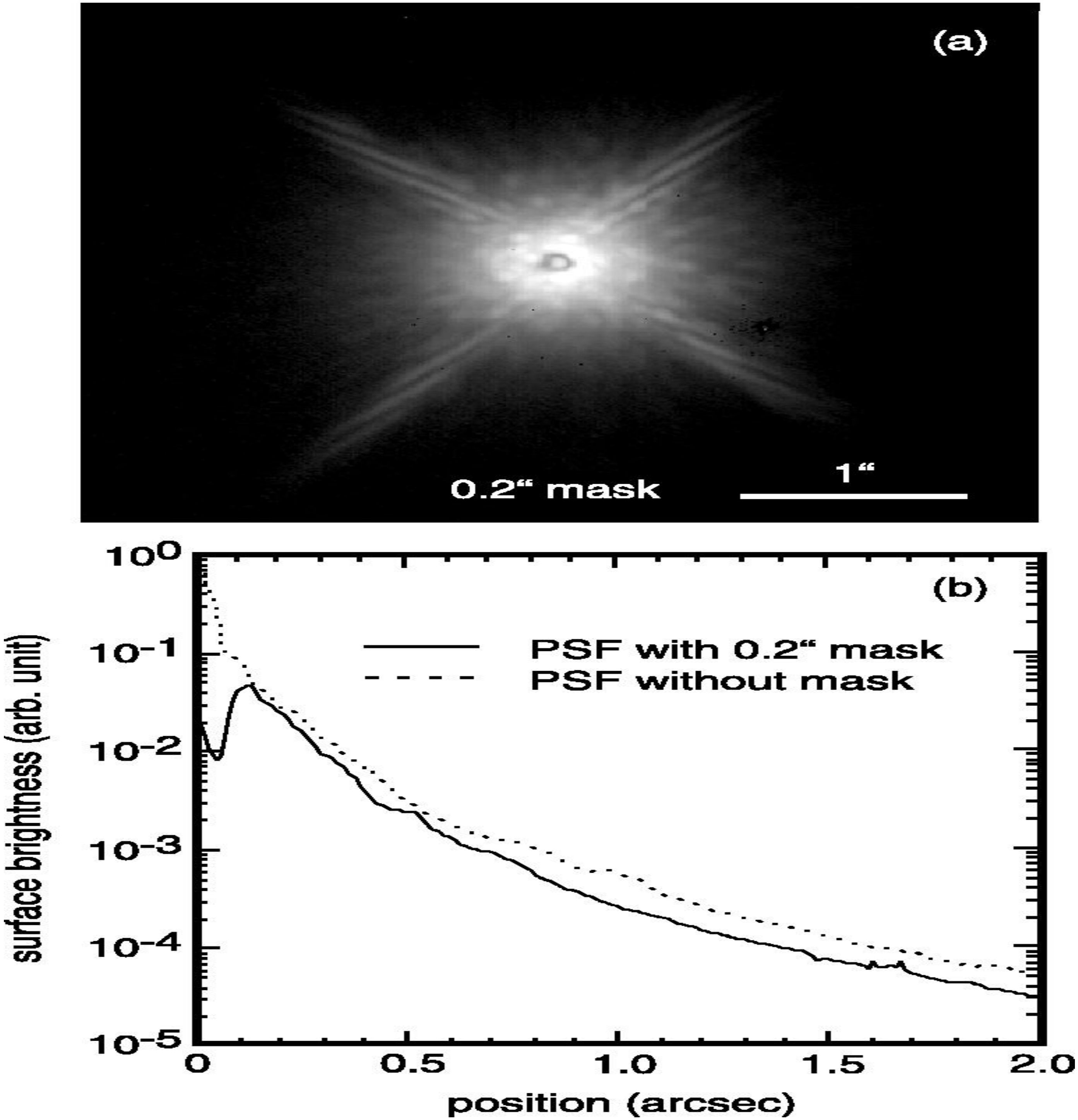
The main advantage of such coronograpgs were to reduce the scattering of light inside the camera and limiting bleeding/blooming of the CCD columns (see the Coronograph of Paul Kalas above).

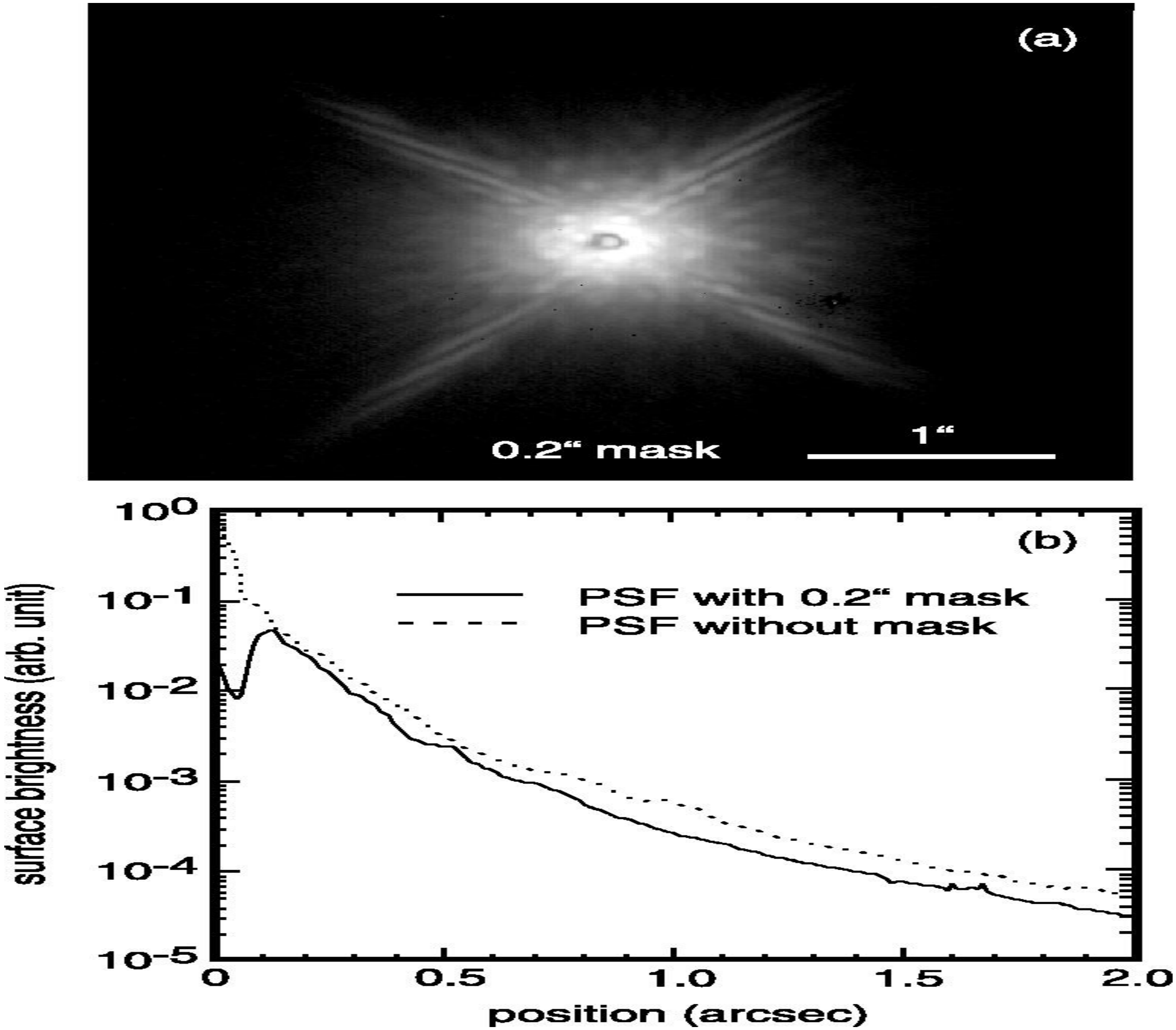
As is now clear however, much larger gains in contrast could be achieved by increasing the Strehl with AO


Companion
Primary star
Telescope
Occulting mask
Collimator lens
Lyot stop
Camera lens
Detector
Log Intensity
Primary (before mask)
Primary (after mask)
Companion
1
0
Transmission of mask
Telescope focus
Linear Intensity
Primary star
Companion or w/o mask
1
0
Transmission of Lyot stop
pupil
Pupil plane
Log Intensity
Primary star w/o mask
Primary star w/ mask
Companion
Final image plane

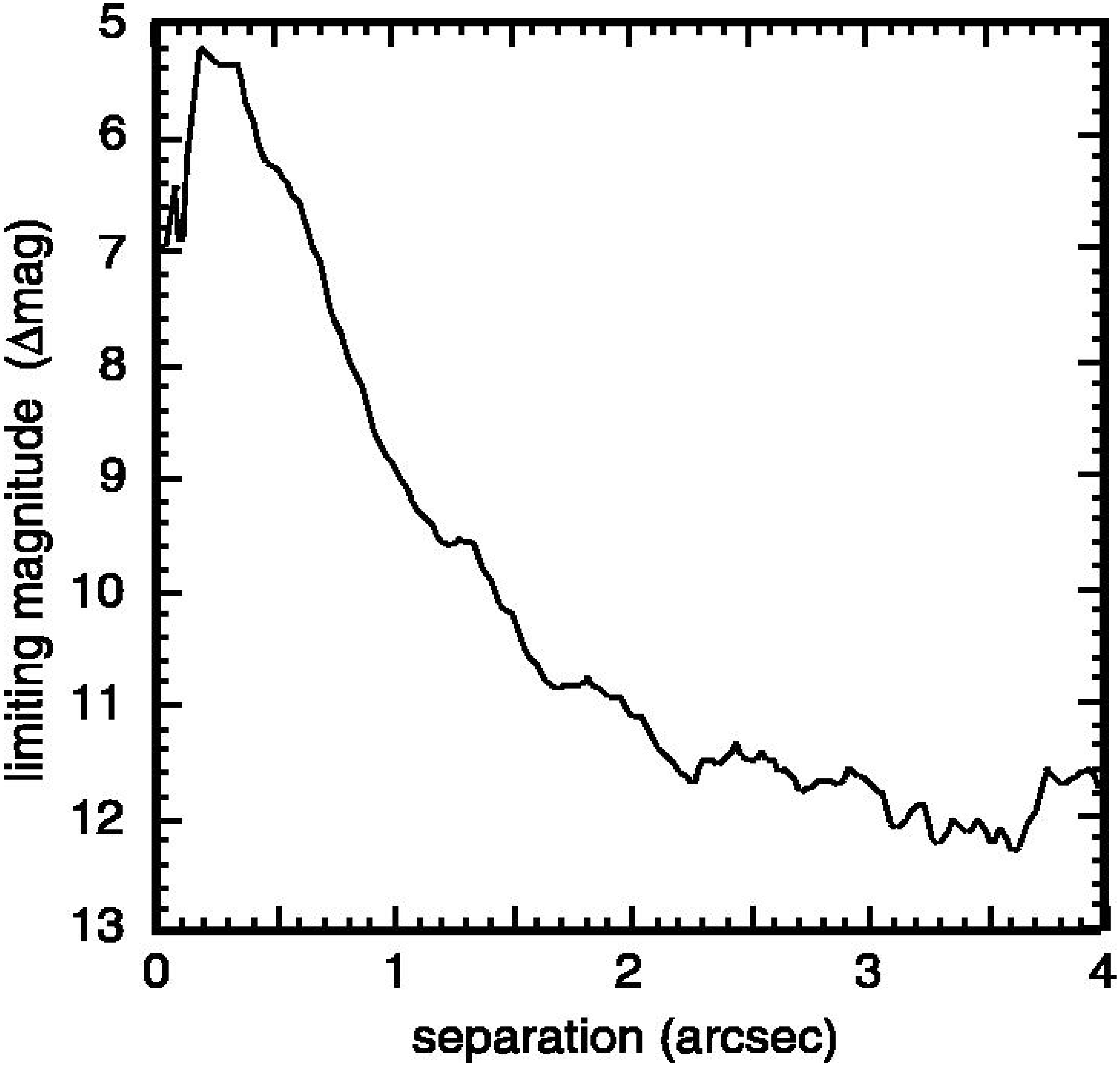


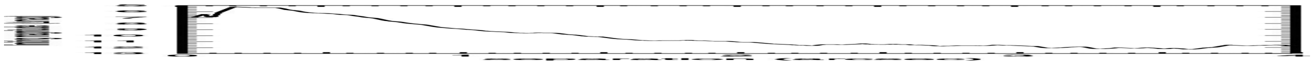
Above we see a simple cartoon of the Subaru AO coronagraph (Murakawa et al. 2004).
Below we see a real example of a ~10% Strehl image on an AO Coronographs of the CIAO coronographic camera at Subaru.
Note how much of the PSF scatters around the coronographic stops.


(a)
0.2" mask
1"
(b)
PSF with 0.2" mask
PSF without mask
surface brightness (arb. unit)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.5
1.0
1.5
2.0
position (arcsec)

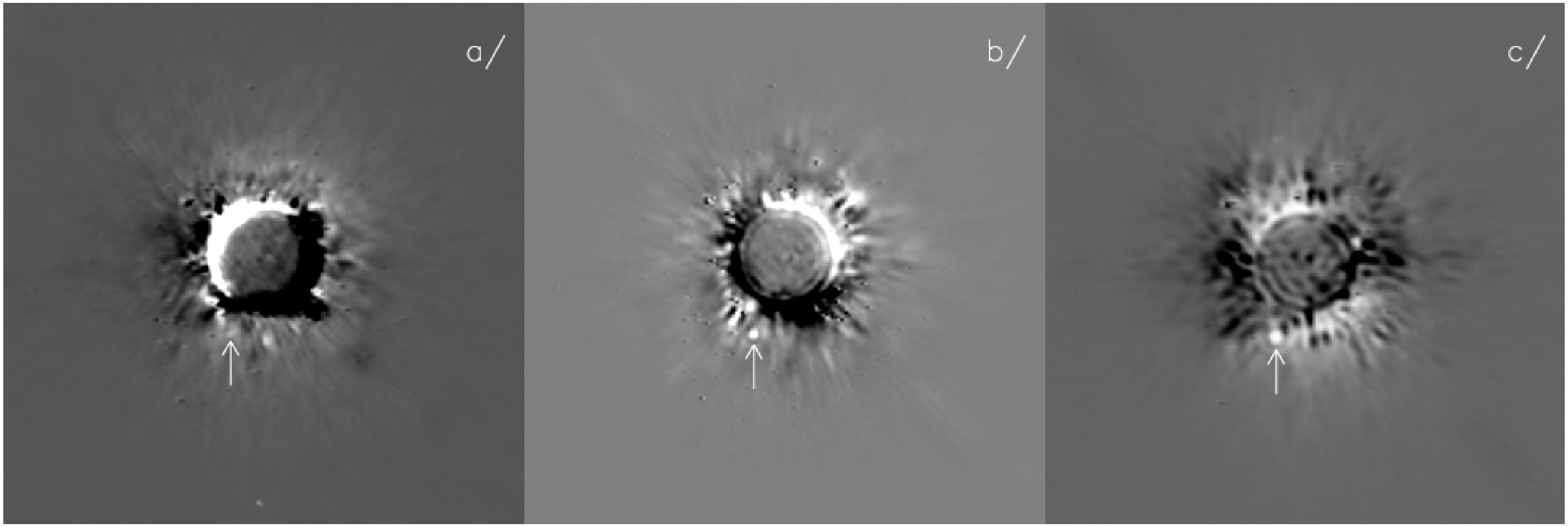


The real coronographic gain at 10% Strehls is pretty poor. Mainly scattering in the camera is reduced. The problem is that at SR~10-20% the Airy rings (which can be suppressed by the coronagraph) are not the dominate source of noise in the halo --- the scattered "super-speckles" are a much bigger noise source!

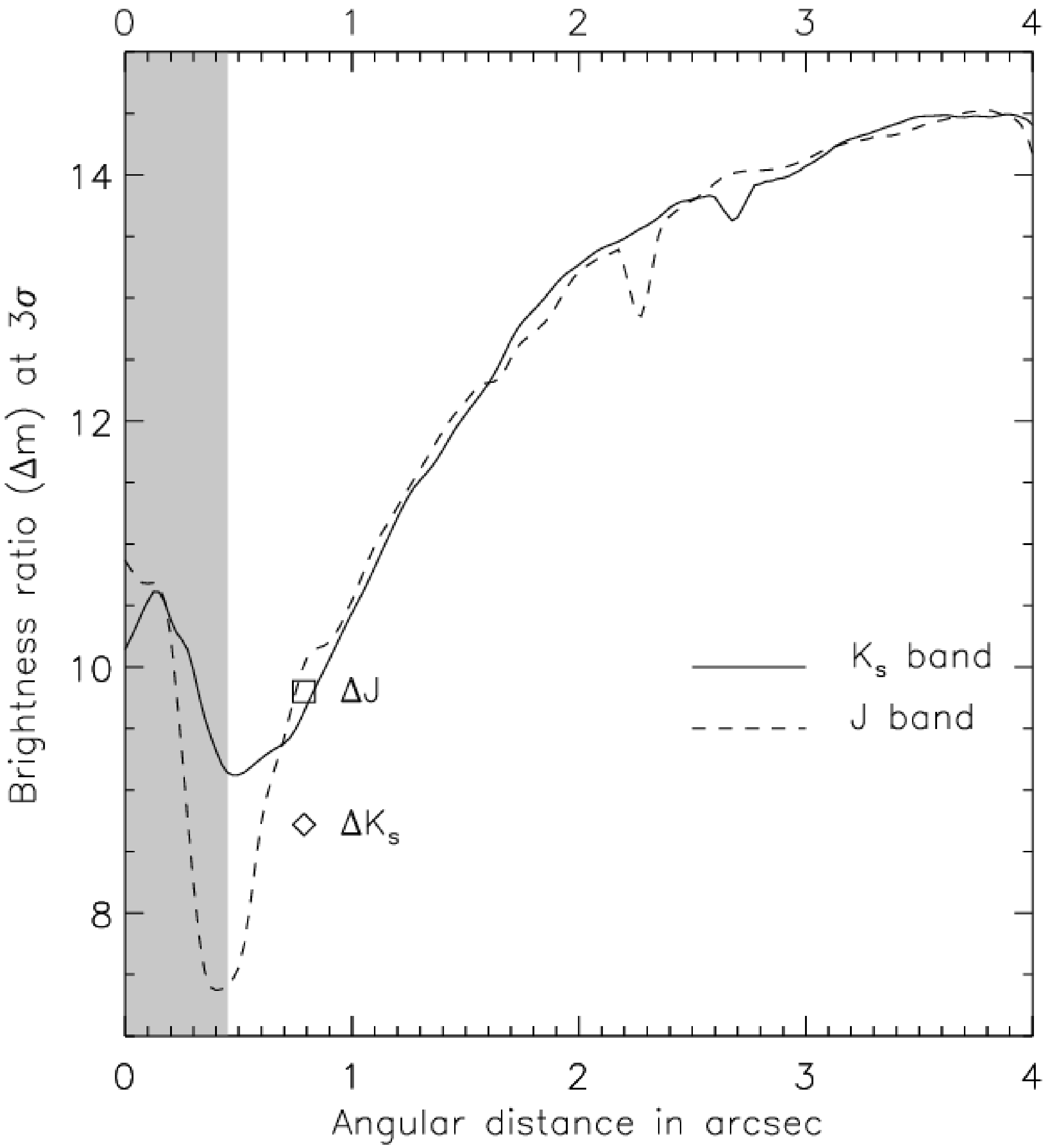




Since the Strehls are ~10-20% the contrasts are modest inside 1".



At higher ~40% Strelhs (K) with AO at the Hale 5m (PALAO) one can achieve better contrasts
note the 51-70 Mjup companion HR 7672B shown above (Boccaletti et al. 2004). (Note HR 7672B was found by Liu et al. 2003 at Keck and Gemini without a coronograph.)



However, there is still the need for a very large mask, and the contrasts are still not what we'd like inside 1".

Higher order D/d AO sampling - see Ben's "Lyot project" talk Friday...

another non-coronographic approach: Simultaneous (Spectral) Differential Imaging

The SDI (Simultaneous Differential Imaging) technique is currently an optimal approach to high-contrast AO imaging.