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Near Infra-Red Astronomy with Adaptive Optics and Laser Guide Stars at the Keck Observatory

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ABSTRACT

A laser guide star adaptive optics system is being built for the W. M. Keck Observatory's 10-meter Keck II telescope. Two new near infra-red instruments will be used with this system: a high-resolution camera (NIRC 2) and an echelle spectrometer (NIRSPEC). We describe the expected capabilities of these instruments for high-resolution astronomy, using adaptive optics with either a natural star or a sodium-layer laser guide star as a reference. We compare the expected performance of these planned Keck adaptive optics instruments with that predicted for the NICMOS near infra-red camera, which is scheduled to be installed on the Hubble Space Telescope in 1997.

Keywords: adaptive optics, laser guide stars, infra-red astronomy, Keck Observatory

1. INTRODUCTION

The W. M. Keck Observatory is designing and building a laser guide star adaptive optics system optimized for observations in the wavelength range from 1 to 2.2 microns. The architecture of the adaptive optics system is described in another paper in this Proceedings[1]. The sodium-layer laser guide star system[2] will be similar to one recently installed at the Lick Observatory[3]. In the present paper we focus on the astronomical capabilities of the Keck adaptive optics system with two new instruments being built for adaptive optics use: the NIRC 2 imaging camera[4], and the NIRSPEC echelle spectrograph[5].

After a brief description of the adaptive optics and laser systems, we discuss the predicted performance of the two new astronomical instruments: their limiting magnitudes, spatial resolutions, and spectral resolutions. For these estimates we employ calculations of the expected point-spread functions produced by the adaptive optics system, together with the measured sky backgrounds at the Mauna Kea site. Finally, we compare the predicted performance of the Keck infra-red adaptive optics instruments with that of the planned NICMOS camera for the Hubble Space Telescope.

2. KECK ADAPTIVE OPTICS OVERVIEW

The Keck adaptive optics system will be placed at the 10-meter Keck II telescope. It will use a continuous face-sheet deformable mirror with about 350 actuators, together with a 64 x 64 pixel bare-CCD, low-noise wavefront sensor. The optical bench is designed so that the astronomical object can be in the center of the field of view, with the reference star off-axis if necessary. Capability will be available for on-chip nodding, to facilitate background-subtraction and the calibration of IR sensor non-uniformities. Wavefront reconstruction will be via a Power-PC based multi-processing real-time computer. The optical bench and real-time computer will be located on the Nasmyth platform, which is a stable, horizontal room-sized platform which rotates in azimuth with the telescope.

A sodium-layer laser guide star will be available for use as a wavefront reference, when suitable natural guide stars are not in the field of view. A pulsed dye laser will provide light at the sodium wavelength, and will be mounted on the telescope. Frequency-doubled Nd:YAG lasers will pump the dye laser on the telescope via optical fibers. Average power of the dye laser is currently baselined at 10 watts, with short-term upgrade capability to 20 watts.

The adaptive optics system will be optimized for operation at wavelengths of 1 to 2.2 microns. However there is expected to be interesting residual capability at observing wavelengths both shorter and longer than this range. The near-infra-red instruments will utilize InSb detectors which are sensitive out to 5 microns; though thermal backgrounds from the uncooled optics will be significant longward of 2 microns, there will be significant astronomy to be done in the range from 2 to 5 microns. At wavelengths shorter than 1 micron the fitting error of the deformable mirror becomes a significant limit to the achievable Strehl, but it should still be possible to produce a diffraction-limited core and to increase the transmission of a spectrograph slit for wavelengths longer than 0.7 microns. This will be discussed further below.

3. INITIAL INSTRUMENTS FOR USE WITH ADAPTIVE OPTICS AT KECK

3.1 The NIRC 2 near infra-red camera

NIRC 2 is an imaging camera[4] designed to be diffraction-limited at 1 micron observing wavelength. It will use a 1024 x 1024 InSb detector array, with pixel scales of 0.01, 0.02, and 0.04 arc sec per pixel. The detector is sensitive from 1 to 5 microns. The camera will have grism spectroscopy capability providing spectral resolution on the order of several thousand, for diffraction limited slit widths. The major technical challenge will be maintaining the alignment of NIRC 2 relative to the adaptive optics bench, to within a fraction of a pixel. This requires alignment stability of a few microns or better.

NIRC 2 will be background limited for broadband imaging, as well as for spectroscopy with spectral resolutions up to R=1000. Therefore, in addition to the increased spatial resolution available via adaptive optics, the limiting magnitude will be improved for point-like sources because each pixel subtends a much smaller area on the sky, hence letting in less sky background. For spectral resolutions greater than R = 1000, between atmospheric OH lines the sky background should be sufficiently low that most of the resolution elements are expected to be dark current limited for integration times less than 10,000 seconds.

Taking into account both of these effects, faint object spectroscopy should be greatly enhanced with use of adaptive optics, due to the smaller image size and higher resolution achievable with NIRC 2. Key scientific objectives include diffraction limited imaging of high redshift galaxies, and studies of the nuclear regions of nearby dusty active galactic nuclei.

3.2 The NIRSPEC near infra-red spectrograph

NIRSPEC is a cross-dispersed echelle spectrograph[5] for high-resolution spectroscopy throughout the 1 - 5 micron region. The spectrograph is planned to have three operating modes: 1) Without adaptive optics, the cross-dispersed echelle will yield spectral resolution R = 25,000 using a 0.4 arc sec slit width. 2) With the addition of adaptive optics the slit width will be decreased to 0.1 arc sec, yielding a spectral resolution of R = 100,000. A second camera will be implemented to achieve the appropriate pixel scale for this resolution. 3) A low resolution mode (R = 2000) will be provided for faint objects, using a slit width of 0.4 arc sec and no adaptive optics. This capability is achieved by inserting a flat mirror into the beam at the location of the echelle grating, so that the cross-disperser grating then serves as the primary dispersing element.

When it operates at a spectral resolving power large enough ($R \geq 20{,}000$) to isolate the atmospheric OH lines in the near infra-red, NIRSPEC's predicted sensitivity is dark current limited at wavelengths less than 2 microns. At longer wavelengths it will be background limited, due to thermal emission from the telescope and optics.

Key projects for the R = 25,000 mode will include long-slit spectroscopy of external galaxies and of our own Galactic Center, kinematics of the environments surrounding young stellar objects, and stellar spectroscopy. Introduction of the high-resolution R = 100,000 mode using adaptive optics will enable for the first time the study of infra-red interstellar molecular absorption lines, to determine the chemical and physical structure of dark clouds. It will also introduce the capability to measure Zeeman splitting of stellar spectral lines, so as to observe stellar magnetic field strengths directly.

A technical issue for the high-resolution mode of NIRSPEC will be how much light is transmitted through the 0.1 arc sec slit, given the point spread functions achieved with the planned adaptive optics system.

4. PREDICTED POINT-SPREAD FUNCTION AND SPECTROGRAPH SLIT TRANSMISSION

4.1 Point spread function

Figure 1 shows the predicted point-spread functions for several observing wavelengths, assuming that 271 actuators of the continuous face-sheet deformable mirror are independently controlled. (Because of the need for a "guard band" of mirror actuators, a 350 actuator deformable mirror has fewer than 350 degrees of freedom. The exact configuration of active actuators has not yet been finalized for the Keck system.) These point spread functions have been calculated using techniques described in Reference 6, and are valid for a bright natural reference star. Both the object being observed and the reference star are assumed to be on-axis in this calculation.

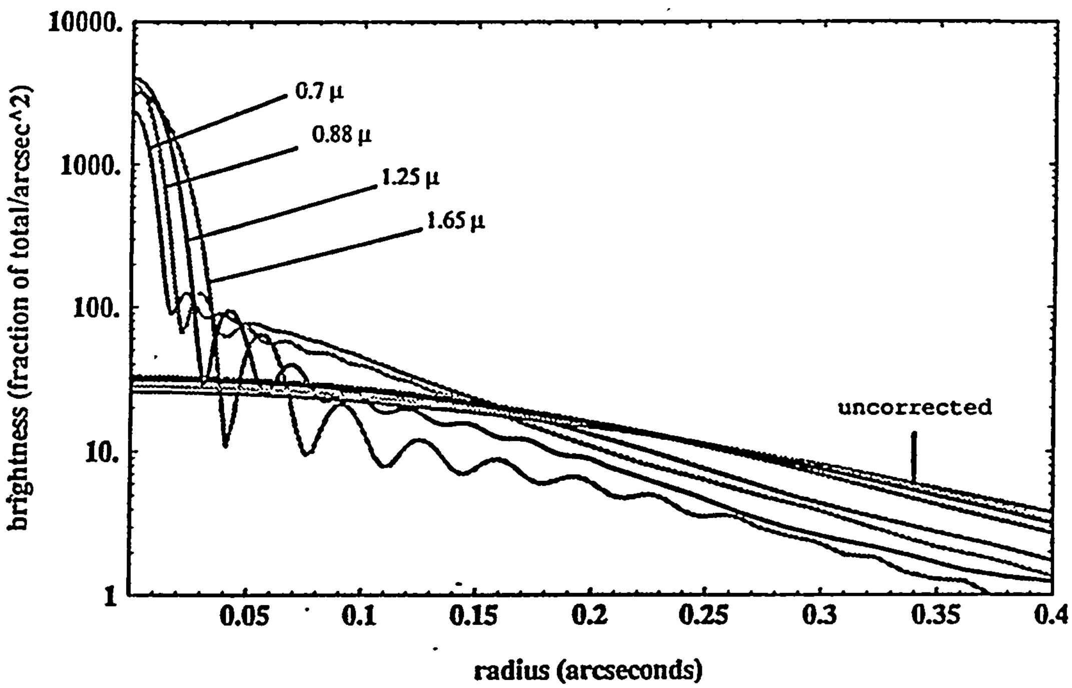

Figure 1. Predicted point spread functions for observing wavelengths of 0.7, 0.88, 1.25, and 1.65 microns, assuming an adaptive optics system with 271 controlled degrees of freedom, inter-actuator spacing of 66 cm mapped to the primary mirror, and Fried atmospheric coherence length $r_0 = 20$ cm at 0.5 microns. The four broad curves labeled "uncorrected" correspond to the point spread function in the absence of adaptive optics. The point-spread functions with adaptive optics have maxima at the left side of the graph, which are diffraction-limited cores at the four respective wavelengths. Several diffraction rings can be seen for the longest wavelength, 1.65 microns, which is closest to being diffraction-limited.

These point-spread functions evidence the typical "core-halo" structure expected of adaptive optics systems operating at moderate Strehl ratios. The halo represents atmospherically scattered light which is not corrected with an adaptive optics system of only 271 degrees of freedom. For images with sufficiently high signal-to-noise ratio in the diffraction limited core, image deconvolution techniques can be used to remove some of the blurring due to the residual halos of the point-spread function. However, such deconvolution techniques require knowledge of the actual point-spread function at the time the image was recorded. To facilitate this type of image deconvolution, the Keck adaptive optics system will maintain a record of the atmospheric turbulence conditions during an observation. These turbulence measurements can be used "after the fact" to calculate an approximation to the actual point-spread function, for use in image restoration routines.

It can be seen from Figure 1 that decreasing fractions of the total light are found in the diffraction-limited core, as the observing wavelength gets shorter. This is of consequence for the amount of light expected to be transmitted through a spectrograph slit, such as those on the NIRSPEC or NIRC 2 instruments.

4.2 Spectrograph slit-transmission fraction

Figure 2 uses the point-spread functions shown above to calculate the encircled energy fractions, as a function of diameter for a point source image. The five curves shown on the left correspond to observing wavelengths of 0.7, 0.88, 1.25, 1.65, and 2.2 microns, with the use of a 271 degree of freedom adaptive optics system as described above. The flatter diagonal curves at lower right are the corresponding encircled energy fractions in the absence of adaptive optics correction.

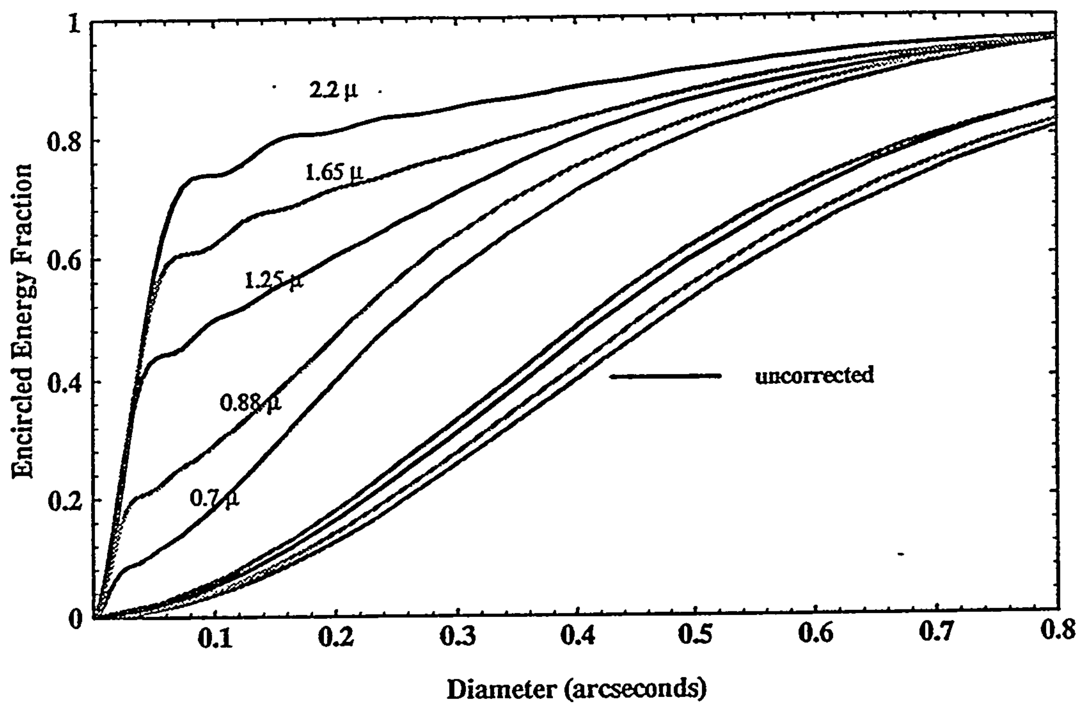

Figure 2. Predicted encircled energy fraction. The curves shown at left correspond to observing wavelengths of 0.7, 0.88, 1.25, 1.65, and 2.2 microns, with the use of a 271 degree of freedom adaptive optics system. The lower, diagonal curves correspond to no atmospheric turbulence correction.

In reality the fraction of light transmitted through a slit will be slightly larger than the encircled energy fraction shown above, because of the difference between circular and rectangular geometries. However, to a first approximation we can use Figure 2 to get a feeling for the fraction of light that would be transmitted through the 0.1 and 0.4 arc sec slits of the NIRSPEC spectrograph when adaptive optics is used:

TABLE 1. ENCLOSED ENERGY FRACTION WITHIN 0.1 ARC SEC AND 0.4 ARC SEC CIRCLES

	0.1 arc sec circle	0.4 arc sec circle
$\lambda = 2.2$ microns	0.74	0.89
$\lambda = 1.65$ microns	0.62	0.83
$\lambda = 1.25$ microns	0.50	0.80
$\lambda = 0.88$ microns	0.29	0.75
Without adaptive optics	0.04 - 0.06	0.39 - 0.48

The first four rows of Table 1 show enclosed energy fractions with adaptive optics. Several conclusions can be drawn.

First, even for the 0.4 arc sec slit width, use of adaptive optics can increase the slit transmission by 50% or more. However, making use of adaptive optics with the 0.4 arc sec slit involves some design adaptation. The R = 25,000 mode of the NIRSPEC spectrograph has a plate scale of 0.15 arc sec per pixel, so that within a slit width of 0.4 arc sec would lie not only the diffraction limited core but also a significant amount of the halo, as can be seen from Figure 1. Thus the slit would be "under-filled" by the object being observed, particularly at the longer wavelengths where most of the light is in the diffraction-limited core. An under-filled slit is undesirable from the point of view of spectrograph performance and stability. However, it might be possible to correct for this effect by designing an adaptive optics calibration system which deliberately produces an elliptical or oblong point-spread function to fill the full 0.4 arc sec slit *width* while maintaining improved spatial resolution in the *long*-slit direction.

Second, even *with* adaptive optics the expected transmissions through the 0.1 arc sec slit are 50% or less, at wavelengths ≤ 1.25 microns. Thus one will be obtaining greatly improved spectral resolution (R = 100,000) by using the narrower slit, but at the cost of sensitivity. Given the fact that the science to be addressed in NIRSPEC's highest-resolution mode is truly unique, this loss of sensitivity remains a good trade-off. But one must realize that even with adaptive optics, for the one-micron wavelength range less than half the light incident on the slit will be tranmitted through it.

4.3 Optimum slit width for a background-limited spectrograph

The point spread function after adaptive optics correction consists of a diffraction-limited core and a halo of light scattered into the seeing disk. As the quality of the adaptive optics correction decreases, more and more of the total energy is found outside the core. However, for poor correction there is still some gathering of light toward the central regions, even when a diffraction limited core has not yet formed.

Given this behavior, it is important to consider at what point it is a benefit to narrow the slit of a spectrograph below the seeing-disk size. This is particularly relevant for background-limited observing, since narrowing the slit reduces sky background in addition to potentially increasing spectral resolution.

For background-limited observations, as with the grism mode of NIRC 2 at low spectral resolution ($R \leq 2000$), the optimum slit width is defined as that width which maximizes the signal to noise ratio:

$$SNR = n_S (n_S + n_{bg})^{-1/2}$$

where n_S is the number of signal photons, and n_{bg} the number of background photons. In J band (1.2 microns), the sky background at Mauna Kea has been reported by J. Graham of UC Berkeley (private communication) to be 15.2 magnitudes per square arc sec. If we consider the hypothetical example of observing a point source with J magnitude $m_J = 21.7$, we can compute the signal to noise ratio as a function of slit width, via a technique suggested to us by M. Shao of JPL (private communication). For low order adaptive optics correction the optimum slit width is roughly the seeing diameter; for high order correction the optimum is the diffraction-limited diameter. However intermediate cases show double peaks as a function of the effectiveness of the adaptive optics correction, because of the core-halo nature of the point-spread function.

The result is illustrated in Figure 3. The bottom curve in Figure 3 shows the optimum slit width in arc sec, as a function of the Strehl ratio achieved by the adaptive optics system. The abrupt change in optimum slit width near a Strehl of 0.1 (for this particular example) is due to the change of the peak at which the signal to noise ratio is the highest. Above a Strehl of 0.1 the optimum slit width is approximately 1.5 (λ / D). At very low Strehl ratios the optimum slit width is the seeing disk size. Between Strehls of 0.01 and 0.1, the optimum slit width slowly decreases, as the partial adaptive optics correction decreases the effective size of the seeing disk. The middle curve in Figure 3 shows the corresponding enclosed energy fraction within the slit. The top curve (on a different scale) shows the signal to noise ratios achieved, expressed as a fraction of the SNR expected with no adaptive optics correction.

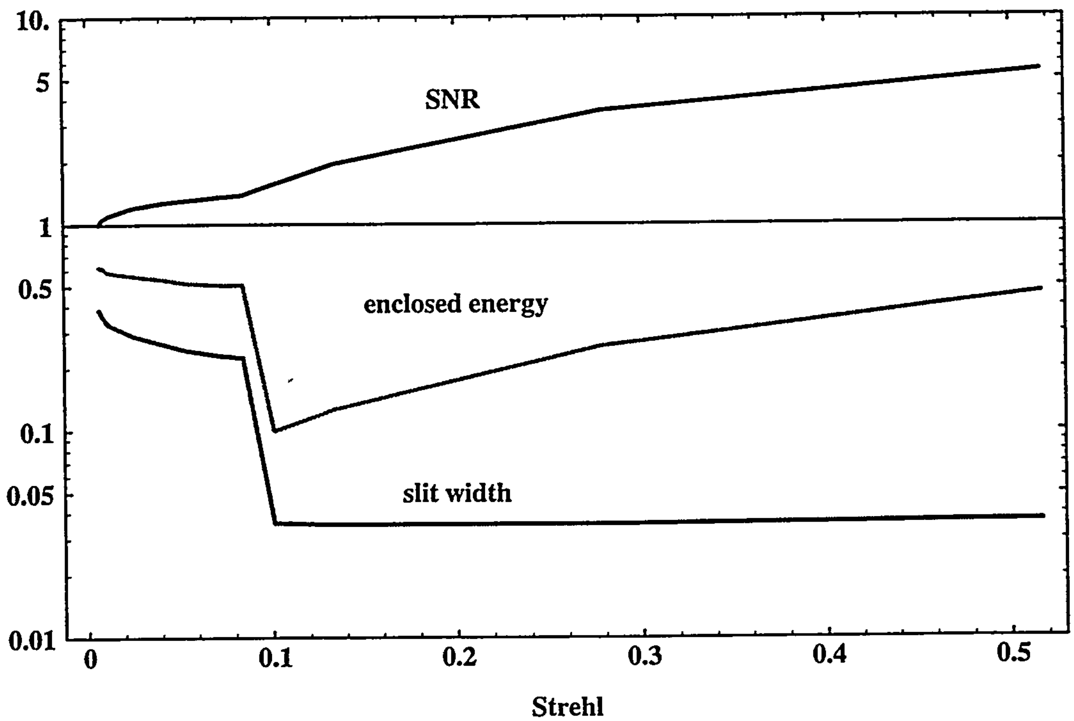

Figure 3. Slit width and enclosed energy fraction to achieve optimum signal to noise ratio, assuming background limited spectrograph performance for $\lambda = 1.2\ \mu m$, $m_J = 21.7$, background J = 15.2 / arc sec^2.

Figure 3 re-emphasizes the advantages of Keck's plans to maintain knowledge of the atmospheric conditions and of the Strehl performance of the adaptive optics system throughout a night's observing schedule. With this sort of up-to-date information, graphs similar to Figure 3 for the current observing conditions can be used to optimize the signal to noise ratio, and hence the sensitivity, of spectroscopic observations by giving guidance on the optimum choice of slit width.

5. PREDICTED LIMITING MAGNITUDES FOR THE NIRC 2 AND NIRSPEC INSTRUMENTS

5.1 Limiting magnitude for NIRC 2 in broadband imaging mode

An important advantage of the ten-meter aperture of the Keck Telescopes is the ability to gather a great deal of light. However as noted above, the limiting magnitude observable by a telescope is determined not only by the strength of the astronomical *signal*, but also by the nature of the *noise* sources. When the predominant noise source is sky background, the detected noise in a pixel increases with the projected size of that pixel on the sky. Adaptive optics can potentially improve the signal-to-noise ratio and hence the limiting magnitude, by putting the light from point-like astronomical sources into a much smaller area on the sky. One can take advantage of this for spectroscopy by using a smaller slit width as described in the last section, together with small detector pixels which match the high resolution of the adaptive optics system. A choice of pixel size is built into the design of the NIRC 2 instrument, both for imaging and for spectroscopic modes. This enables the observer to collect fewer sky-background photons than would be the case in the absence of adaptive optics.

The NIRC 2 camera is expected to be sky-background limited in its broadband imaging modes. It takes advantage of the physics described above by use of 0.01, 0.02, or 0.04 arc sec pixel scales, which can be selected so as to maximize the signal to noise ratio for a given observing wavelength and adaptive optics system performance. For a one-sigma detection in a 10^4 second integration time, Reference 4 predicts a limiting magnitude for NIRC 2 of about K = 28 mag (observing wavelength of 2.2 microns).

5.2 Limiting magnitudes for the NIRSPEC spectrograph

NIRSPEC is in a different physical regime from NIRC 2 in its two high-spectral-resolution modes, R = 25,000 and R = 100,000. In these modes NIRSPEC is dark-noise limited rather than background limited, because the narrower spectral band-pass restricts the number of background photons incident on the detector.

Using the methods described in Reference 5, we can calculate the corresponding limiting magnitudes predicted for NIRSPEC, both with and without adaptive optics. For these calculations we use the slit transmissions expected for the appropriate adaptive optics corrections, as well as the number of pixels which sample the eighty-percent enclosed energy fraction for a point-like source in the long-slit direction. The results are given in Table 2, assuming a 3600 second integration time and a signal to noise ratio of 10. Results for different integration times and signal to noise ratios may be scaled appropriately.

TABLE 2. PREDICTED LIMITING MAGNITUDES FOR THE NIRSPEC SPECTROGRAPH

Observing mode	$\lambda = 1.25\ \mu m$	$\lambda = 2.2\ \mu m$
R = 25,000; no AO	J = 18.8	K = 18.0
R = 25,000; with AO	J = 19.8	K = 19.0
R = 100,000; with AO	J = 17.3	K = 17.4

6. PERFORMANCE COMPARISON OF KECK WITH ADAPTIVE OPTICS AND HUBBLE SPACE TELESCOPE WITH THE NICMOS CAMERA

The Hubble Space Telescope (HST) is scheduled to be retro-fitted with a near infra-red camera, NICMOS, during a refurbishing mission planned for 1997. The Hubble Space Telescope is a 2.4 meter diffraction-limited instrument. NICMOS will use a 256 x 256 HgCdTe detector. Compared with ground-based telescopes, Hubble has the obvious advantage that it is above the earth's atmosphere, and can thus avoid atmospheric turbulence problems.

In this section we compare the expected performance of the Hubble Space Telescope NICMOS camera with that predicted for the Keck telescope adaptive optics system using the NIRC 2 and NIRSPEC instrument. We are grateful for the help of C. Skinner of STScI (private communication) in outlining the NICMOS capabilities for the purpose of this comparison.

6.1 Angular resolution

The diameter of the Keck telescope is more than four times larger than that of the HST. Hence if the Keck adaptive optics system were to perform *perfectly*, its angular resolution (e.g. as measured by λ / D) would be at least four times better than that of HST at the same observing wavelength. For example at a wavelength of 2 microns, the diffraction-limited resolutions of Keck and HST are 0.04 arc sec and 0.17 arc sec respectively.

In practice the "ideal" diffraction-limited performance will be achieved frequently at Keck for wavelengths of 2 microns, and less often at wavelengths near 1 micron where adaptive optics Strehl ratios are not expected to be so high. In the latter case a quantitative comparison of Keck with HST depends on the specific performance measure one is interested in.

This is illustrated in Figure 4, which shows the full width at half maximum (FWHM), together with the 50% and 80% enclosed energy diameters, as a function of the number of degrees of freedom of the Keck adaptive optics system. The observing wavelength is 1.25 microns. For 271 controlled degree of freedom, Figure 4 shows that the Keck FWHM is its diffraction-limited value, the 50% enclosed energy diameter is about 50% larger than the FWHM, and the 80% enclosed energy diameter has only been reduced to about 60% of the original size of the seeing-disk without adaptive optics.

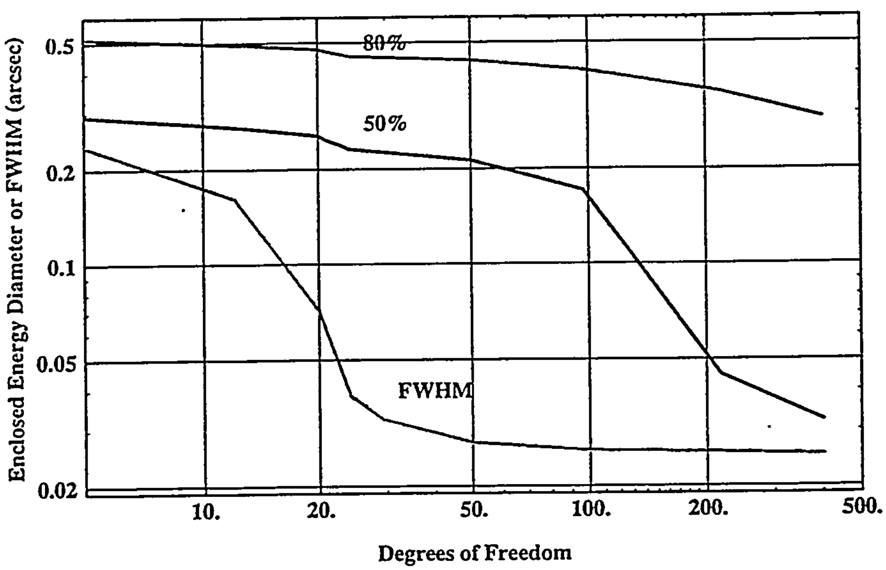

Figure 4. Enclosed energy diameters and full width at half maximum (FWHM) predicted for Keck adaptive optics with varying numbers of controlled degrees of freedom. Turbulence parameters are as in Figure 1.

For comparison recall that at 1.25 microns, λ / D for HST is equal to 0.1 arc sec. Because of Keck's much larger size, its angular resolution is likely to be considerably better than that of HST despite the peculiarities of the "core-halo" PSF.

6.2 Point spread function

The Keck adaptive optics point spread function (PSF) will not be as well-behaved as that for HST. We emphasized in Figure 4 that adaptive optics creates a characteristic "core-halo" shape for the PSF. As turbulence in the atmosphere varies with time, the fraction of energy in the core and halo will change. The design of the Keck adaptive optics system includes provision for continuously recording atmospheric conditions, so as to enable after-the-fact reconstruction of the PSF. But this reconstruction will not be ideal. The point spread function of HST with NICMOS is expected to be much more stable.

6.3 Field of view

We shall show in this section that the high-resolution field of view is not very different for Keck than for HST with NICMOS. The usual unfavorable limitation due to isoplanatic angle is balanced by the larger number of pixels at Keck, and by the benign scaling of adaptive optics performance at infra-red wavelengths.

First, consider the limitation on field of view caused by the finite number of pixels in the relevant infra-red array detectors. NICMOS's 256 x 256 detector used with the camera of appropriate pixel scale yields a field of view of 11 arc sec at 1 micron observing wavelength. At Keck the NIRC 2 camera has a 1024 x 1024 array. Use of 0.01 arc sec pixels (Nyquist sampled at 1 micron) yields a field of view of about 10 arc sec, comparable with that of NICMOS at 1 micron.

At longer wavelengths, larger pixel scales can be selected both for HST and for Keck by changes in the camera optics. For HST the broadest field of view is 51 arc sec, suitable for a wavelength of 2.2 microns. For Keck, use of 0.02 and 0.04 arc sec pixel scales yields a field of view of 20 and 40 arc sec respectively, a bit smaller than that for HST.

Second, ground-based adaptive optics systems also must face the limitation which the isoplanatic angle places on the effective field of view. In practice the isoplanatic limitation is not a "hard" one: depending on the science one is interested in, one can utilize a lower Strehl ratio over a larger area, or a higher Strehl ratio over a smaller area. Figure 5 illustrates this effect for the planned Keck adaptive optics system. It plots the Strehl ratio achieved at the edge of the field (compared to the on-axis Strehl ratio) as a function of the field diameter, for several observing wavelengths.

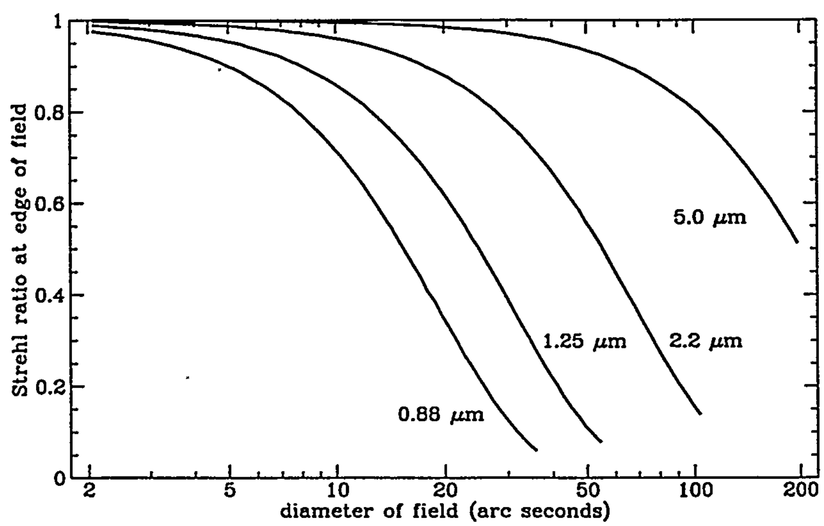

Figure 5. Reduction in Strehl ratio at edge of the field of view compared to on-axis Strehl, as function of the angular diameter of field at the Keck telescope.

At a wavelength of 1.25 microns, Keck's Strehl has fallen by a factor of two when the field diameter reaches about 25 arc sec. This diameter is well larger than the 10 arc sec limitation determined by the number of pixels in the Keck array at its highest resolution. Thus for wavelengths of 1 - 1.25 microns, it is the array size rather than the isoplanatic angle which determines the Keck field of view, yielding a diameter of about 10 arc sec which is comparable to that of NICMOS.

At an observing wavelength of 2.2 microns, Keck's Strehl has fallen by a factor of two at the edge of the field when the field diameter reaches about 55 arc sec. In this case the limitation due to the Keck array size is again more stringent than that due to isoplanatic effects, since the largest angular size of the Keck array is about 40 arc sec (and for this pixel scale the PSF is not Nyquist sampled at 2.2 microns). By comparison the largest angular size of the NICMOS field is slightly larger, 51 arc sec.

We conclude that with the available infra-red arrays for HST and NICMOS, in most cases it will be the array size rather than the isoplanatic angle which limits the field of view. Taking the array sizes and pixel scales into account, the fields of view of Keck and HST will not be very different in the near infra-red.

6.4 Sky coverage fraction

Because of its orbital coverage, HST has virtually 100% sky coverage potential. On the other hand the sky coverage for Keck with sodium-layer laser guide star adaptive optics will depend on the existence of a ~19'th magnitude tip-tilt guide star within the iso-kinetic field of view.

This effect has been discussed quantitatively in References 6 and 7. The results show that with a laser guide star and the planned Keck adaptive optics system, the effective sky coverage fraction at Keck should be in the range of 40 - 50% on the average. Hence HST has a definite advantage over ground-based telescopes with respect to sky coverage. The use of sodium laser guide stars makes the HST's advantage a factor of two to three, rather than the several orders of magnitude which would apply for *natural* guide star adaptive optics.

6.5 Wavelength coverage

In the area of wavelength coverage, HST and Keck have complementary advantages.

First, consider detector and instrument response. HST's HgCdTe detector cuts off at wavelengths longer than 2.2 microns, while the Keck InSb detector remains sensitive out to 5 microns. The Keck system will begin to suffer from enhanced thermal backgrounds at wavelengths longer than about 2 microns, both because of the telescope and because of the many additional optical surfaces introduced by the adaptive optics system. However, for bright enough sources Keck will still have interesting long-wavelength capability, while HST will not.

Second, we must consider the effects of the atmosphere. Keck will not be able to see through the high-atmospheric-absorption bands at 1.3 - 1.5 microns and at 1.8 - 2 microns, whereas HST has no such limitations. Thus NICMOS will make genuinely new contributions in these wavelength bands, compared with *all* ground-based telescopes.

6.6 High-precision photometry

HST's more stable point-spread function should give it an inherent advantage in doing precision photometry. By contrast, for Keck the time variations of the point-spread function and the spatial variation of Strehl ratio within the field of view will make precision photometry more difficult. Availability of real-time information concerning the atmospheric turbulence parameters will help users to develop methods for compensating for these effects, but it is not yet known to what photometric precision these methods will work.

On the other hand, for photometry of faint objects Keck may have some advantages. First, its large aperture and superior limiting magnitude are clearly beneficial. But in addition, the HST NICMOS pixels have gaps between them, which some fear will make quantitative faint-object photometry more difficult. Experience will be needed with both systems before it is clear which of these effects will be serious in the long run.

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