Publications of the Astronomical Society of the Pacific, 112:315–319, 2000 March

Research Note

First Light Adaptive Optics Images from the Keck II Telescope: A New Era of High Angular Resolution Imagery

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Received 1999 October 8; accepted 1999 December 16

ABSTRACT. Adaptive optics (AO) is a technology that corrects in real time for the blurring effects of atmospheric turbulence, in principle allowing Earth-bound telescopes to achieve their diffraction limit and to "see" as clearly as if they were in space. The power of AO using natural guide stars has been amply demonstrated in recent years on telescopes up to 3–4 m in diameter. The next breakthrough in astronomical resolution was expected to occur with the implementation of AO on the new generation of large, 8–10 m diameter telescopes. In this paper we report the initial results from the first of these AO systems, now coming on line on the 10 m diameter Keck II Telescope. The results include the highest angular resolution images ever obtained from a single telescope (0".022 and 0".040 at 0.85 and 1.65 μm wavelengths, respectively), as well as tests of system performance on three astronomical targets.

The Keck adaptive optics (AO) facility is located on the left Nasmyth platform of the Keck II Telescope (Chanan et al. 1996; Wizinowich et al. 1998). The images presented here, except for Figure 2, were obtained with an engineering camera whose detector is a 256 × 256 pixel, 17 mas pixel^{-1}, NICMOS3 array. AO systems use a sensor to measure the distortions of the incoming wave front and a deformable mirror to correct for these distortions. The Keck AO wave front sensor is a Shack-Hartmann type with 2 × 2 pixels per subaperture and frame rates between 80 and 670 Hz. The 349 actuator deformable mirror is conjugate to the telescope's primary mirror with the actuator spacing corresponding to 56 cm on the primary. A technical description of the Keck AO system will be published elsewhere.[1] The first light image obtained with the Keck AO system on the night of 1999 February 4 dramatically illustrated the capability of this system. The uncorrected image, taken at 1.65 μm wavelength (*H* band), had an FWHM of 600 mas. The AO-corrected image had an FWHM of 44 mas and, for a brief time (see below), represented the highest resolution AO-corrected image ever obtained.

The increase in performance is demonstrated in Figure 1, a three-dimensional plot of intensity versus position in the image plane for an uncorrected and corrected *H*-band image taken on the second night of AO observing. The ratio of corrected to uncorrected peak intensities is 50, and the corrected image FWHM is 40 mas versus 340 mas without correction. The Strehl ratio, the ratio of the peak of the corrected image to that of a perfect diffraction-limited image, is 30%. At shorter wavelengths, the Strehl of the corrected image is reduced, while the angular resolution is improved. This is demonstrated in Figure 2, taken at

[1] A general description of AO systems can be found in Beckers (1993). A bibliography of refereed AO astronomy papers can be found at http://www2.keck.hawaii.edu:3636/realpublic/ao/ao_sci_list.html.

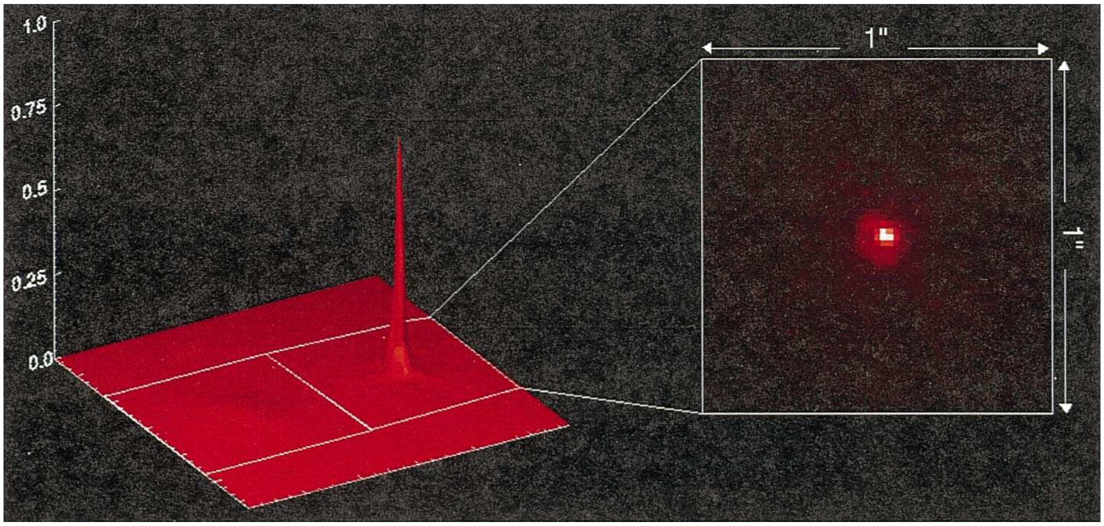

FIG. 1.—Intensity vs. image plane position plots, at left, of an uncorrected (small bump) and AO-corrected (high peak) stellar image of a 9th magnitude star taken in H band on 1999 February 6. The FWHM decreased from 340 mas to 40 mas while the peak intensity, or Strehl ratio, increased from 0.6% to 30%. A 1″ × 1″ display of the corrected, 16 s integration, image is shown on the right.

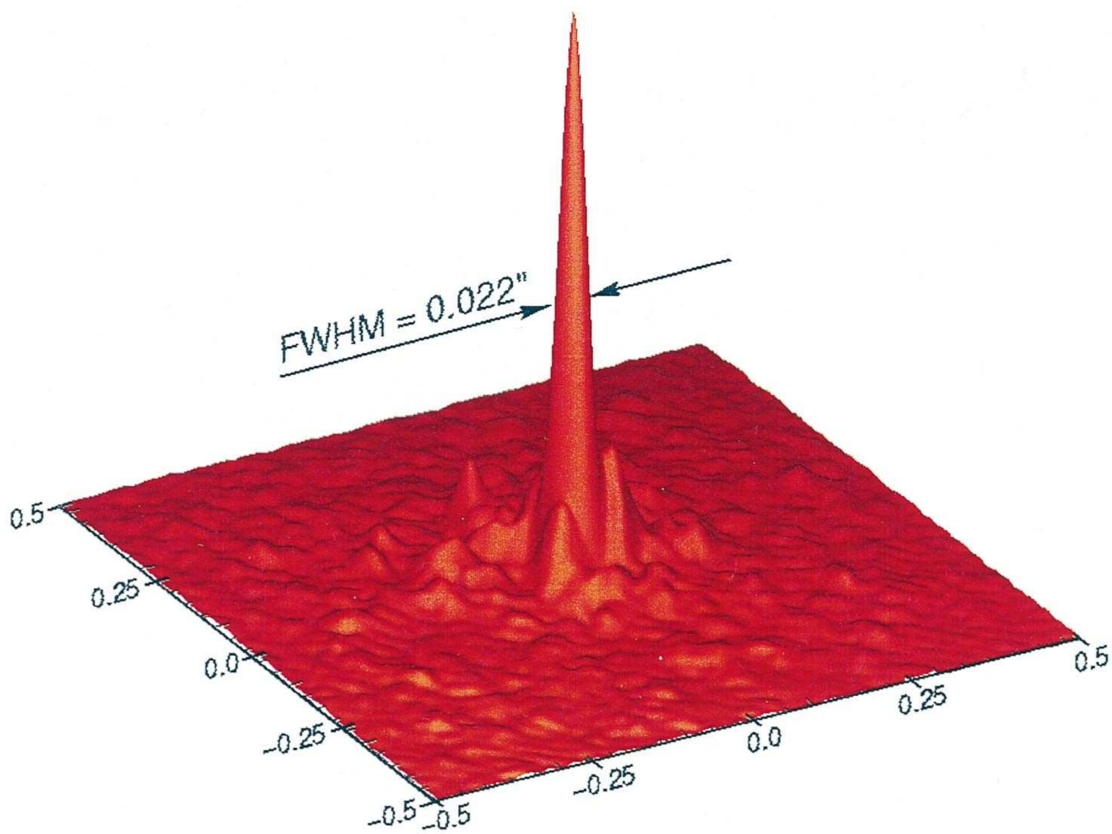

FIG. 2.—This 1″ × 1″, 10 ms exposure of a 4.5 mag star was obtained on 1999 April 2 with the AO acquisition camera using a 10 nm wide, 850 nm wavelength filter and a plate scale of 7.5 mas pixel^{-1}. The Strehl ratio is 6% for this short exposure. This is believed to be the highest resolution in the visible/near-infrared regime ever obtained via direct imaging.

0.85 μm wavelength, which shows the highest angular resolution image, 22 mas FWHM, of a celestial source obtained to date with a single telescope.

Astronomical AO systems must perform well on a variety of types of images. Notable among these are large, low-contrast objects such as planets, crowded fields of point sources such as star clusters, and extragalactic objects. The Keck AO commissioning process included performance tests on these important classes of astronomical targets.[2] The infrared images in this paper were, unless otherwise noted, processed with only standard infrared techniques (sky subtraction, flat-fielding, dead pixel correction, and correlated noise removal) using the Keck AO data reduction pipeline (Lai, Wizinowich, & Gathright 1999).

The AO performance on a large extended object, Neptune, observed in the methane absorption band at 1.17 μm on 1999 May 24 is illustrated in Figure 3. A simulated uncorrected image, in 400 mas seeing, is also shown for comparison. Neptune proved to be an excellent AO guide object despite its large angular size (2″.3). The bright region on the right is a prominent storm measuring 150 mas (3100 km on Neptune) in both longitude and latitude. The sharp bottom border of this storm and the narrow width of the circumferential bands give a measure of the spatial resolution achieved by the AO system, of order 40 mas. Quantitative modeling of the vertical distribution of atmospheric hazes within the storm, versus "normal" haze and methane distribution, can be performed since the size of the storm is clearly resolved. The bright circumferential bands on Neptune resemble those seen at visible wavelengths by the *Voyager 2* spacecraft (Hunt, Moore, & Hunt 1994; Baines et al. 1995). These bands are unresolved in the AO image, consistent with the *Voyager 2* measurement that they were 50–200 km wide.

Figure 4 demonstrates the AO performance on a star cluster, the crowded region surrounding Sgr A. Sgr A is a radio source thought to mark the position of a black hole at the center of our Milky Way galaxy. Figure 4 is a mosaic of 4″.4 × 4″.4 images obtained at 2.1 μm wavelength (K' band) on 1999 May 26 with a total integration time of 2 minutes. This was a particularly challenging object since the 13.2 visual magnitude guide star is located 30″ from the position of Sgr A. This demonstrates the use of a relatively faint guide star and shows that the isoplanatic angle, the angular distance from the natural guide star (NGS) over which good correction is obtained, can be quite large. The corrected images have an FWHM of 40 mas and show no evidence of degradation from the center to the edge of the field.

The inset image of Figure 4 shows the stars in an 800 × 800 mas region in the immediate vicinity of Sgr A. Similar resolutions had previously been obtained with speckle observations at Keck (Ghez et al. 1998). However, because of the higher Strehl with AO, twice as many stars

[2] Images of some of the objects observed with the Keck AO facility can be found at http://www2.keck.hawaii.edu:3636/realpublic/ao/aolight.html.

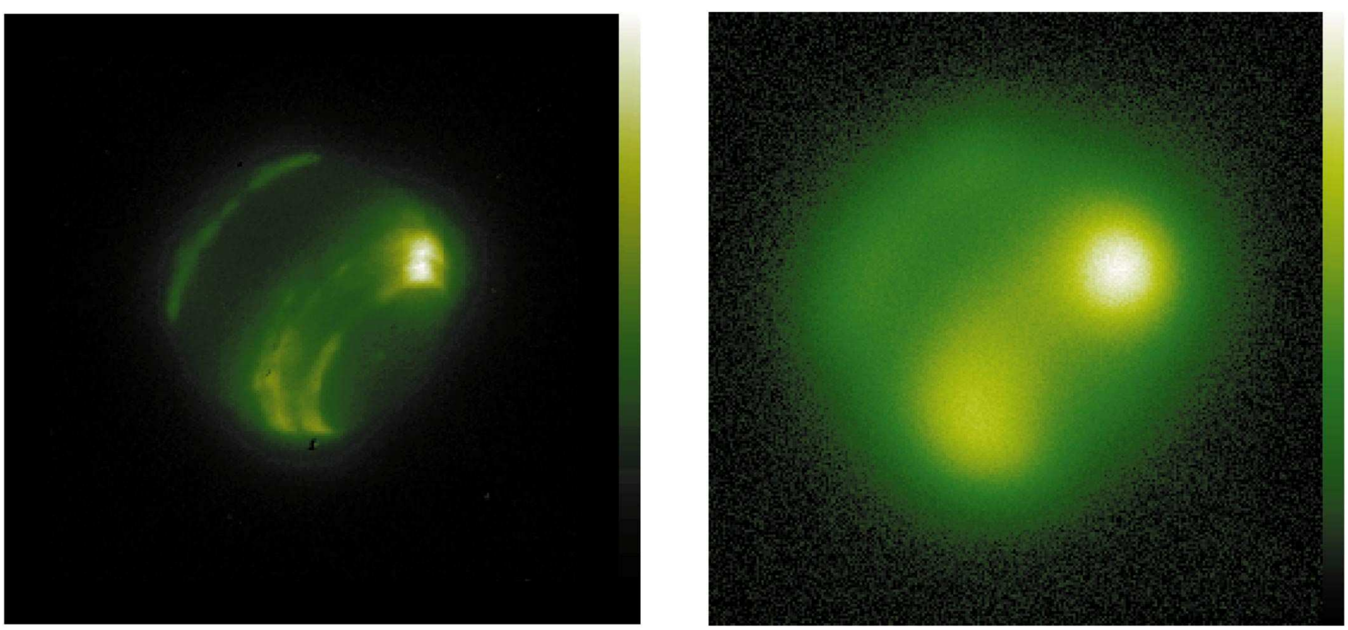

FIG. 3*a* FIG. 3*b*

FIG. 3.—Neptune was observed on the night of 1999 May 24 in several wavelength bands. (*a*) A 9 minute AO-corrected exposure in the methane absorption band (1.17 μm). (*b*) Uncorrected image in 400 mas seeing shown for comparison. Neptune is 2″.3 in diameter. A very powerful storm in the upper atmosphere, at center right, was observed to rotate from right to left.

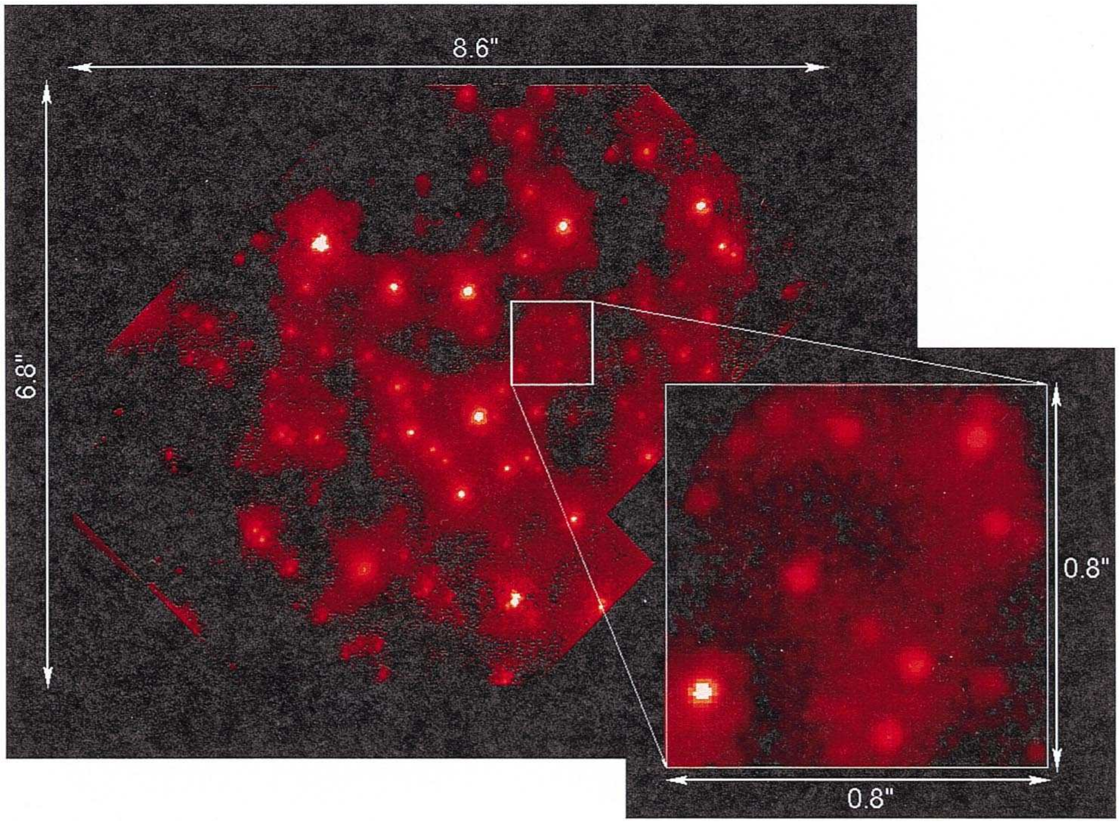

FIG. 4.—Image of the Galactic center obtained from a mosaic of 24 images (total integration time of 2 minutes) taken on 1999 May 26. The inset image (90 s exposure) of the central 800 × 800 mas area will be used to help determine the mass of the possible central black hole located at the position of the radio source Sgr A.

are seen in this inset than were previously observed with speckle. The stars in this region are known to have extremely high velocities, some as high as 1400 km s^{-1}, due to their motion in the gravitational potential of the black hole. Repeated observations of each star's position over several years will permit a determination of the stellar velocities. The velocity field is a very strong indication of the mass enclosed in the central 0.3 pc of our Galaxy.

The Galactic center image was "halo-cleaned" in addition to standard cosmetic infrared processing. This is a technique where the residual halo is modeled and the inverse of its Fourier transform is used as a high pass filter. This preserves the photometry of the original images while increasing the contrast of each detected source. The *K*-band Galactic center image on the Canada-France-Hawaii Telescope (CFHT) Web page[3] was processed in the same manner. Comparison of the 15 minute CFHT and 1.5 minute Keck images reveals the same number of sources. The angular resolution is higher in the Keck image (0″.06 vs. 0″.14), while the Strehl ratio is higher in the CFHT image (65% vs. 25%).

[3] http://www.cfht.hawaii.edu/Instruments/Imaging/AOB/best_pictures.html#galactic_center.

A unique type of observation made possible by the Keck AO system is the imaging of faint field galaxies. These observations make use of the high density of galaxies on the sky rather than the density of a bright NGS. On average there are two galaxies brighter than 20th *K* magnitude within 20″ of any star. These objects form a statistically unbiased set of compact galaxies at high redshift, corresponding to roughly half the present age of the universe, and provide an excellent sample for studying galaxy evolution. Because of their great distance, these galaxies are very compact, 1″–4″, with typical scales of 0″.1–1″, and are only marginally resolved with traditional ground-based techniques. The *Hubble Space Telescope* has been very successful at studying compact galaxies at optical resolutions as high as 100 mas, but these images are biased toward strong sources of ultraviolet radiation. Infrared images taken with the Keck AO system can achieve even higher resolution and give a more accurate picture of the older stellar population and morphology. Given the faintness and size of these galaxies, this project is feasible only for a large telescope with an AO system delivering high Strehl ratios. The Figure 5 inset shows one of two galaxies imaged with the Keck AO system. The galaxy has a total *H*-band magnitude of 19 and a 2″ extent. The image has

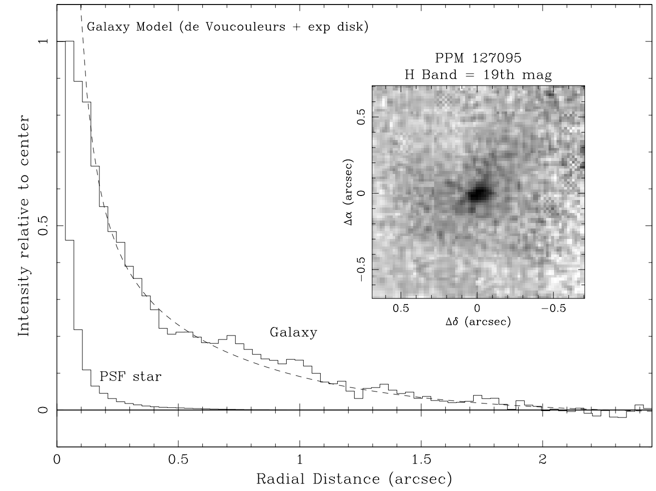

FIG. 5.—The inset shows the highest resolution image of a faint galaxy ever taken. The original 20 minute exposure has a resolution of 50 mas. The 2″.8 × 2″.8, displayed image has been binned by 2 × 2 pixels to give 35 mas pixel^{-1}. The plot is a radial profile of the galaxy and PSF star. The dashed curve is a standard galaxy model fitting the bulge and disk separately.

been binned 2 × 2 pixels from the original image to give a resolution of 35 mas pixel^{-1}. The resolution of the original image was 50 mas, representing the highest resolution infrared image of a faint galaxy ever obtained. The galaxy is 18″ from a 10.2 mag NGS (PPM 127095). A second star 17″.9 from the NGS was used to measure the point-spread function (PSF). Non-AO imaging marginally resolved the object in good seeing conditions, 400 mas, but no morphological information was available. The AO image represents 20 minutes of integration time with an off-axis Strehl ratio of about 10%. Figure 5 also shows an azimuthally averaged radial profile of the galaxy and the PSF. The smooth curve is a model profile consisting of a standard $r^{1/4}$ profile for the central bulge and an outer exponential disk. The central flattening of the profile is typical for many bulges and is not included in the model. This preliminary fitting suggests that this is an inclined disk galaxy consistent with a morphological class of Sb or Sc. We hope to additionally determine the surface brightness of the disk and bulge and look for asymmetries that might have resulted from tidal interactions. Within the next year, with new spectrographic capabilities, we plan to search for active galaxies, study the stellar population ages, and measure the rotation curves of these objects.

The Keck NGS AO facility became available for general observing in 1999 September. The system is still being optimized to achieve the performance predicted by the error budget (Strehl ratio of 0.62 at *H* band under median seeing conditions for a bright star) (Wizinowich 1996). In particular, the image diameter should be reduced by about 6 mas to the diffraction limit (34 mas at *H* band), thereby also increasing the Strehl, through improvements in the global tip/tilt performance. During 2000, we plan to integrate the AO system with two science instruments and to implement a sodium laser beacon to dramatically increase the sky coverage with this AO facility.

We would like to acknowledge the contributions of the following individuals: past and present members of the Keck Observatory staff, especially F. Chaffee, J. Chock, R. Cohen, A. Conrad, M. Dahler, M. DiVittorio, A. Gleckler, T. Gregory, K. Kinoshita, H. Lewis, D. McBride, D. Medeiros, R. Moskitis, M. Sirota, T. Saloga, K. Sweeney, and T. Williams; the wave front controller team at LLNL: H. Bissinger, R. Hurd, E. Johansson, B. Johnston, H. Jones, M. Newman, K. Waltjen and J. Watson; James Larkin and Ian McLean (UCLA) for providing the engineering science camera; and the Keck adaptive optics science team. The W. M. Keck Foundation provided funding for the AO facility, with additional funding from NASA and LLNL.

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