

Coronagraphic imaging: Keck II AO and HST ACS compared

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1. Introduction

High contrast imaging is necessary to search for and study sub-stellar objects and debris disks surrounding bright stars. Here we compare the performance of coronagraphs used with ground-based adaptive optics (AO) systems to those implemented in HST science cameras. The following data are used in the present investigation:

1. With Keck II (10 m) AO, we used the coronagraphic mode of the NIRC2 science camera (1024×1024 InSb array). NIRC2 has 10 focal plane occulting spots between 100 mas and 2000 mas diameter, five selectable pupil plane stops, and three selectable plate scales. The V=8.8 star HD 162052 was observed at K', with a 300 mas focal plane mask, a pupil plane mask matched to the telescope pupil (large hexagonal), 120 sec cumulative integration time, and with 0.01"/pix plate scale. Measured Strehl ratios are S~50%.
2. For HST ACS, we adopted the performance specifications for the F606W filter given in the Cycle 12 Instrument Handbook Version 3.0. John Krist also supplied us with the F606W coronagraphic images of Arcturus shown in Chapter 5 of the ACS Instrument Handbook (offspot and onspot, with the High Resolution Channel Lyot mechanism in place).

2. PSF Differences

In general, PSFs have static and temporal characteristics, and are composed of both scattered light (the seeing halo) and diffracted light (the Airy disk). The encircled energies of the Keck AO and the HST ACS data are shown in Fig. 1. Keck AO produces near diffraction-limited central cores (FWHM = 54 mas), but the uncorrected atmosphere contributes a scattered seeing halo beyond 0.1" radius ($2.5 \lambda / D$) that contains ~40% of the light.

A coronagraph should have the following effect on the PSF:

- Light scattered into the seeing halo by the atmosphere or by the Optical Telescope Assembly (OTA) is not suppressed.

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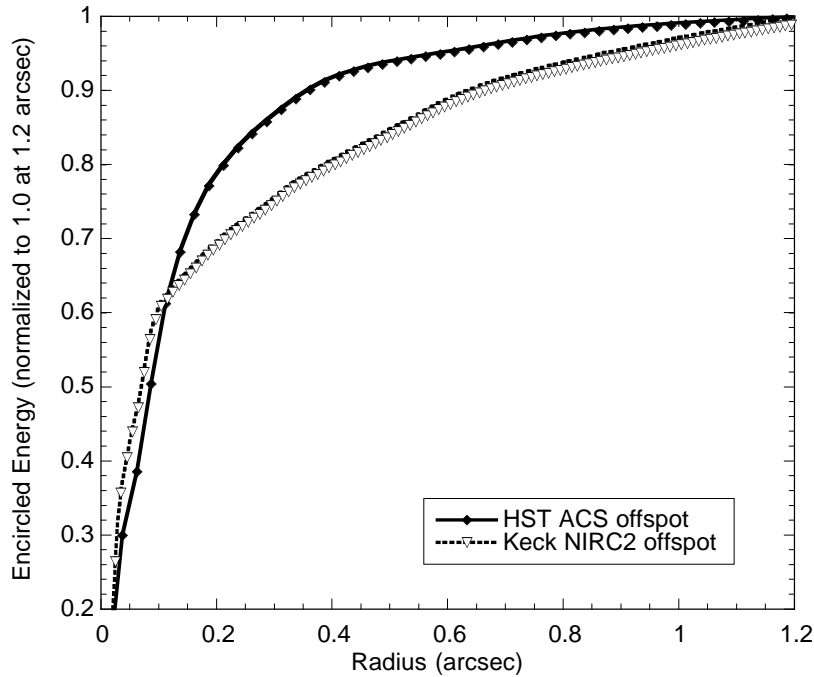


Figure 1. Encircled energies for the stars used to test coronagraph performance, before occultation by a focal plane occulting mask.

- Scattered light within the science camera is suppressed because the PSF core is absorbed by the focal plane occulting mask.
- Diffracted light due to the OTA is suppressed, depending on the sizes of the Lyot stop *and* the occulting spot. The larger the occulting spot, the more light is pushed to the edges of the pupil plane image, which is then masked by the Lyot stop.

Based on these principles, the *a priori* expectation is that the ACS coronagraph will further diminish the intensity of the PSF wings shown in Fig. 1 because the PSF is dominated by diffraction. Ground-based, AO coronagraphic data should demonstrate only modest improvement over a non-coronagraphic observations because the seeing halo is dominated by atmospheric scattered light.

3. Coronagraph Suppression

Figure 2 is made by taking the median azimuthal value for each occulted PSF as a function of radius, and converting it to a relative magnitude based on the peak intensity of the star in an unocculted image. We find that the coronagraph suppresses the AO PSF wings by a median value of 0.6 mag in the range $0.2''$ – $1.2''$ radius. Thus the suppression of instrumental and diffracted light by the coronagraph gives a somewhat unexpected contrast gain for AO images. The ACS coronagraph suppresses the PSF by a median value of 1.5 mag in the range $1.0''$ – $3.0''$ radius.

Overall, the differences between HST and Keck when comparing the occulted (spot) or unocculted (offspot) PSFs are not significant. Clearly the region within $1''$ radius of the star is accessible with Keck AO, whereas the large size (radius $0.9''$) of the smallest ACS occulting spot prevents coronagraphic imaging of the sub-arcsecond region. Recently detected objects follow an envelope just above the PSF curves, indicating that, to first order, a simple radial plot of the PSF corresponds to detection limits.

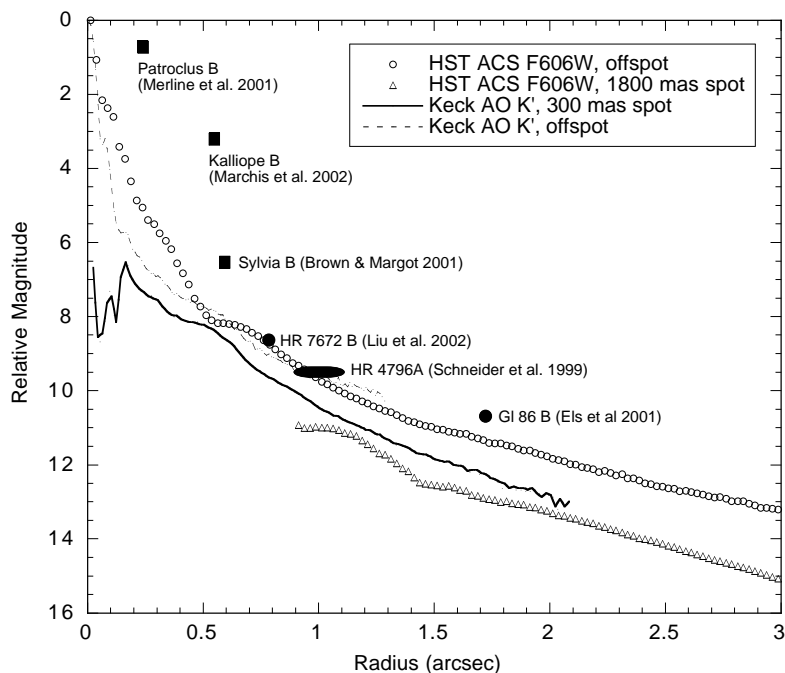


Figure 2. Radial PSF intensity normalized relative to the peak intensity and converted to relative magnitude. Solid circles are sub-stellar objects, solid ellipses are circumstellar disks, and solid squares are asteroidal companions discovered by direct observations with AO systems at Lick, Gemini, and Keck.

4. Detectability Simulations

Ultimately the sensitivity of HST and Keck should be tested by simulating the science objects and working through a variety of observing modes and data reductions (e.g. Kalas & Jewitt 1996, Schneider et al. 2001). A crucial step is subtraction of the PSFs shown in Figure 2 by either self-subtraction after a field roll, or by observing a nearby reference PSF contemporaneously. Because the Keck telescope has an alt-az mount that produces field rotation, we are presently testing the efficacy of roll deconvolution from the ground.

For the present investigation, we merely insert a model dust disk into the coronagraphic PSFs without any further data reduction. The model disk is described in Kalas & Jewitt (1996). We fix the disk inclination (73°), central hole radius ($1''$) and peak surface brightness ($12 \text{ mag arcsec}^{-2}$), to correspond to the HST NICMOS image of HR 4796A (Schneider et al. 1999). The main difference is that the model has no fixed outer extent, whereas the real HR 4796A disk is a confined ring. Fig. 3 shows that the ACS coronagraph would detect the dust scattered light if the disk were in fact extended rather than confined. In addition to detecting the outer disk, Keck AO reveals the boundary for the central hole in the dust distribution.

5. Conclusions and Future Directions

- Coronagraphic imaging reduces the PSF wings by 0.6 mag using Keck AO in the NIR, and 1.5 mag using the ACS coronagraph in the visible. In circumstellar regions where these tests overlap, the occulted and unocculted PSF wings show roughly comparable sensitivity for Keck AO and HST.

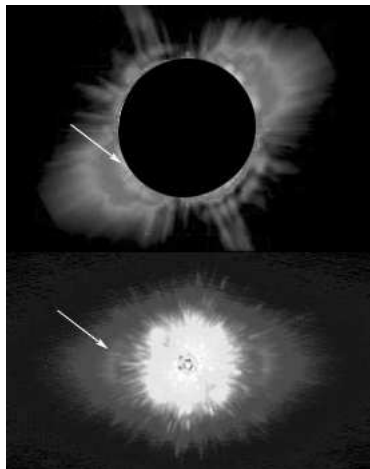


Figure 3. Model HR 4796-like disk inserted into the ACS occulted PSF at PA=135°(top) and into the Keck AO PSF at PA=90°(bottom) . The normal PSF shows an azimuthally symmetric halo, whereas the distortion evident here is due to the circumstellar disk. Arrows designate the brightest portion of the disk within which a central disk hole is present.

- Ground-based AO has the advantage over HST ACS in imaging circumstellar regions within 1'' radius. The HST NICMOS coronagraph has a smaller occulting spot than ACS, but imaging is still limited to $\sim 0.6''$ radius (Schneider et al. 1999). High-order AO systems will further improve the ground-based capability of imaging the sub-arcsecond circumstellar region (Sivaramakrishnan et al. 2001, Lloyd et al. 2001).
- The results shown here have a limited scope. Future work must test the sensitivity gains attained with PSF subtractions and longer integration times. Comparisons of ground-based AO to HST NICMOS and STIS coronagraphic data are also necessary.

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