

Detection of Planets with the Hubble Space Telescope Advanced Camera for Surveys

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Abstract. Under favourable circumstances direct planet detection will be feasible with the new Advanced Camera for Surveys, due for launch on the Hubble Space Telescope in 2001. This may be achieved through direct imaging using the ‘Aberrated Beam Coronagraph’ or through precise astrometric and photometric measurement of appropriate candidates. The α Cen triple star system, and nearest stars to the Sun, have been shown to possess regions in the space about them where planets could survive. Detailed optical simulations of α Cen A indicate that detection of a Jupiter-like planet in six-orbits of images, although difficult, is feasible if the planet is suitably located and systematic effects can be controlled. Meanwhile the proximity and low mass of the brown dwarf Gl 229B, only $\approx 45M_J$, make perturbation of its orbit by Jupiter-sized planets or photometric perturbation due to occultation by even lower mass planets feasible observing programs for the ACS on HST. Burrows et al. are engaged in an initial investigation using the Wide Field and Planetary Camera 2 during the current Cycle.

1. The Advanced Camera for Surveys on the Hubble Space Telescope

The Advanced Camera for Surveys (ACS) is a new instrument currently being assembled for launch and installation on the Hubble Space Telescope (HST) in 2001. The goal is to provide a diverse suite of imaging capabilities with performance, in terms of surveys and “discovery space” representing an increase of over a factor ten for HST (Ford et al. 1996). The ACS science team will use much of its time in pursuit of extragalactic, cosmological survey projects, and in addition will investigate a number of scientific problems uniquely well-suited to the instrumental opportunity afforded by ACS. This includes a twofold search for planets. Firstly, using the coronagraphic option on ACS, direct detection with imaging will be attempted to find Jupiter-like planets around α Centauri, and secondly, using astrometric reflex and precise photometric monitoring, planets of low mass may be inferred around the brown dwarf Gl 229B.

Prof. H. Ford leads the ACS project at the Johns Hopkins University, Baltimore, with science team members from several other astronomical institutions. The primary industrial contractor is Ball Aerospace.

The ACS is really three separate cameras that share optics. There are two optical imagers, a wide field camera (WFC) and a high resolution camera (HRC). The WFC is a high throughput, sensitive, wide-field I -band optimized camera designed for faint survey observations. The camera employs two SiTe CCDs each 2048×4096 pixels butted together to give a 4096×4096 pixel field of view, each pixel ≈ 0.05 arcsec and hence $\approx 200 \times 200$ arcsec areal coverage. The HRC is optimized for blue imaging, critically sampled across much of the optical wavelength region, utilizing a single 1024×1024 SiTe CCD. The camera offers a field of view $\approx 26 \times 29$ arcsec on the sky, and has been specially coated to provide good sensitivity into the near-UV (~ 200 nm).

In addition to the two “optical” cameras, there is a third “solar blind camera” (SBC) which is optimized to provide good sensitivity from 115 to 170 nm, in the far-UV. The detector is a solar-blind CsI Multi-Anode Microchannel Array (MAMA), with 1024×1024 pixels nominally providing a field of view of 31×35 arcsec.

There are a variety of special modes and configurations available, including grism and prism spectroscopy, narrow-band imaging using “linear ramp filters” across the entire optical wavelength range, polarization and coronagraphy.

For the purposes of the present discussion, it is the coronagraphic capability that is of the greatest interest. An overview of the ACS optics, including the predicted performance of the coronagraphic mode is available from STScI in the “Advanced Camera for Surveys Instrument Mini-Handbook” by Clampin et al., with the full ACS Instrument Handbook to be released soon. The so-called “aberrated beam coronagraph” is a module which is attached to the calibration assembly at the entrance aperture of the ACS. It is a moveable mechanism, which, when inserted, simultaneously places two occulting masks in the HST focal plane, while apodizing the beam at the nearby pupil. There is also an occulting finger close to the CCD focal plane to eliminate charge bleeding from the expected bright central spot in extreme cases. Figure 1 shows an image taken through the coronagraphic optics. The two focal plane masks have diameters of 1.8 arcsec and 3.0 arcsec. Their edges are fuzzy because the beam is spherically aberrated at that point, and the images are elliptical due to the tilted optics.

Figure 2 shows the predicted performance of the coronagraph. The wing suppression is quite effective but limited by an inability to correct for mid-range wavefront errors known to exist on the HST mirrors. Additional point spread function (PSF) wing suppression is obtained using “roll-deconvolution”. Using this technique, images are obtained with the telescope at two different roll angles. All the telescope and instrument optics remain fixed and the PSF on the detector remains fixed, however any underlying astronomical target moves with respect to the detector. Hence a simple subtraction, in principle, is an exceedingly powerful way to eliminate many of the complexities of the HST PSF.

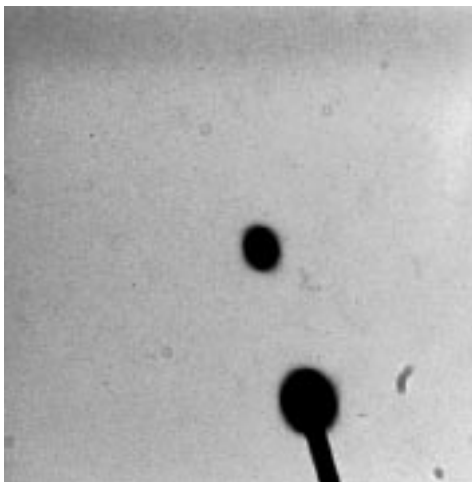


Figure 1. Image taken with ACS coronagraphic optics in beam showing occulting spots of 1.8 and 3.0 arcsec diameter.

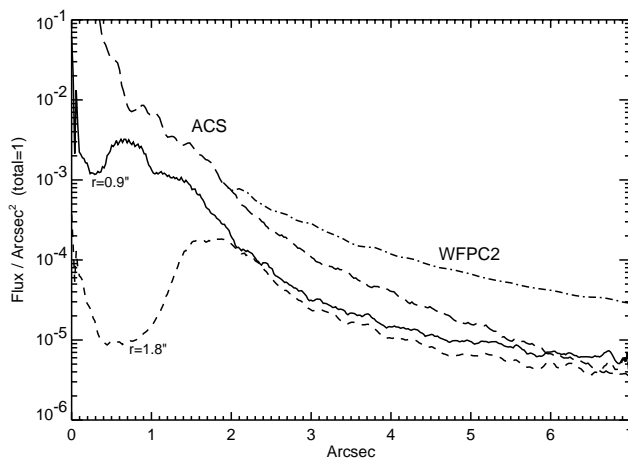


Figure 2. Predicted performance characteristics of the ACS coronagraph. The upper curves show the observed WFPC2 and expected ACS (without coronagraph) PSF profiles. The lower two show PSF profiles with the ACS coronagraph and 0.9 and 1.8 arcsec radius focal plane masks.

2. Scientific Program

Now we discuss specific application of these capabilities to the problem of planet detection in two particular cases.

2.1. α Centauri

The nearest stellar system to the Sun is that of α Centauri, a triple system comprising α Centauri A and B and Proxima Centauri at significantly greater separation. Since it is the nearest star, and it is quite like the Sun (both A and B components), it is an obvious target for planet searches. Hypothetical planets of given properties (contrast ratio, distance from star) will be at wider separation and be brighter in a nearer star, and hence easier to detect. Components A and B are separated by 23.4 AU (semimajor axis) with luminosities 1.6 and 0.45 L_{\odot} respectively.

The fact that α Centauri is a multiple system is a possible complication since this may reduce or remove the dynamical stability of planetary orbits. Benest (1988) and Wiegert & Holman (1997) looked into the question of whether stable orbits could exist within this system. They found that dynamical stability is a strong function of orbital inclination, and with orbits up to about 4 AU from α Centauri A stable over the timescales of numerical integration conducted. A series of longer zero-inclination numerical integrations corresponding to $\sim 10^8$ yr eroded the stable region to about 2.5 AU. However, the stability criterion adopted eliminated as unstable those orbits which migrated significantly in phase space. The curious properties of the known extrasolar planets might give rise to the suspicion that such migrations occur but can leave the planet within the system. In any event, it is plausible from the calculations that stable orbits may exist, and indeed that planets may exist within the habitable region around α Centauri A.

The observing strategy anticipated is roll-deconvolution, described above. Figure 3 shows a simulated set of images of Jupiter placed at the distance of α Centauri. In these simulations, the planet was kept at 5 AU. In the top left panel, a raw PSF image is shown. The bottom two panels show the difference of two sets of three orbits exposure. The lower left is the difference between two perfectly matched PSFs, dominated by photon noise from the subtraction. The hypothetical Jupiter-like planet is readily visible. The lower right, however, shows the subtraction allowing for a small focus change typical of what occurs as the telescope “breathes” around its orbit. The actual focus change shown is on the large side, and it is clear that if such focus (or breathing) changes do occur, the detection of our Jupiter-like planet becomes infeasible. It may be possible through carefully chosen observational timing to mitigate the effects of these focus shifts, and thought must be given to minimizing their presence at the time of observation.

Hence if there is a Jupiter-like planet at a Jupiter-like orbital distance from its host star, and if the observational systematics can be controlled, it will be possible to obtain a direct image of such a planet using the ACS on HST in coronagraphic mode.

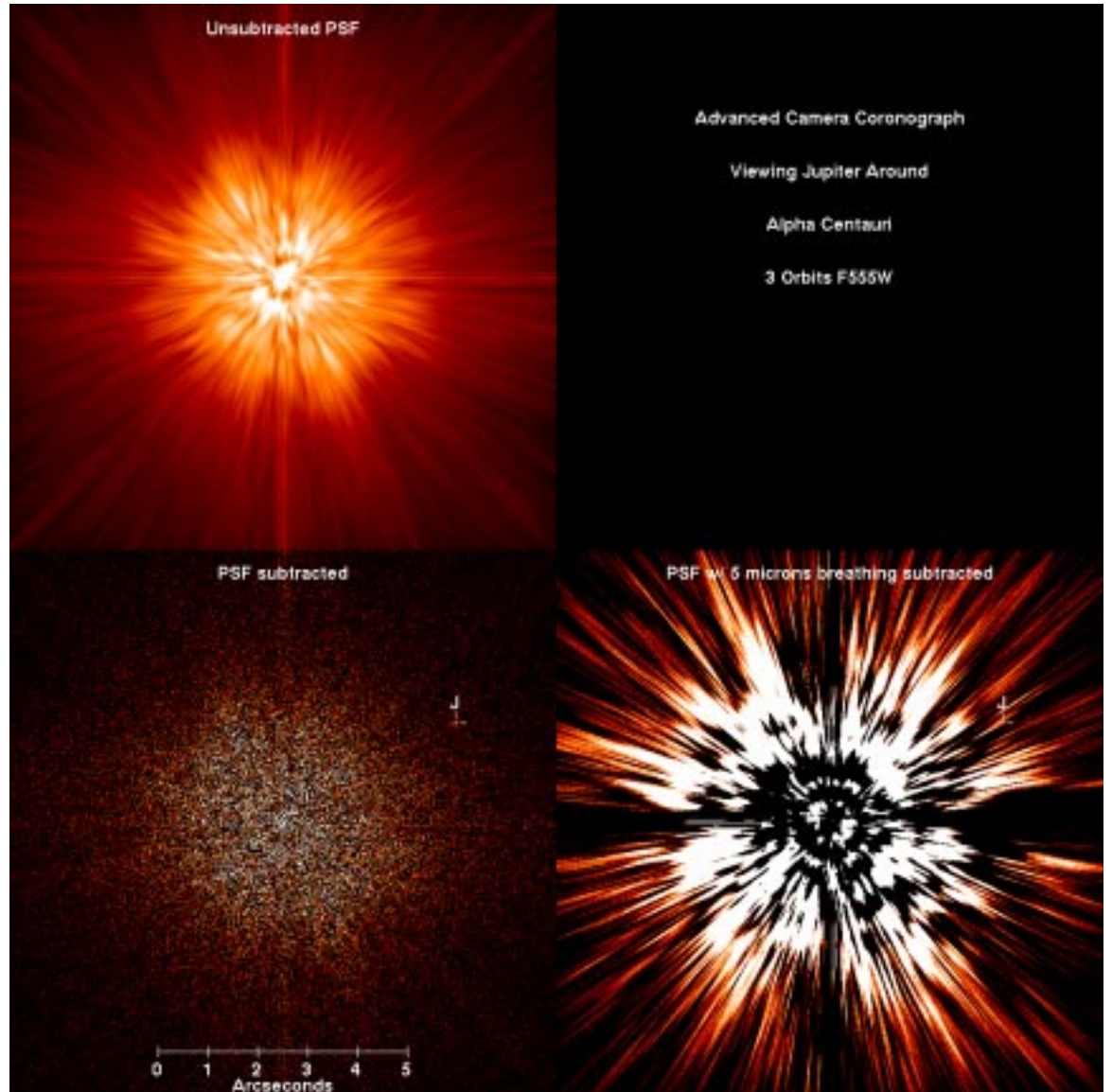


Figure 3. Simulated images of Jupiter-like planet at α Centauri, showing the raw PSF, top, and two pairs of three orbit image subtracted, lower left with perfect focus match, and lower right with five micron focus change.

2.2. Gl 229B

Now we turn to more orthodox techniques for planet detection, but applied in a particularly sensitive circumstance. The brown dwarf Gl 229B, cool enough to exhibit methane absorption, orbits the nearby star Gl 229A. Indeed, there are currently eight methane brown dwarfs known, mostly from the 2MASS and SDSS surveys. To state the obvious, the mass of a brown dwarf is low: only $\approx 45M_J$ (“J” denoting Jupiter) in the case of Gl 229B and their sizes are small, $R \sim 1R_J$.

These two properties may be utilized to offer high leverage on traditional techniques. The low mass of the brown dwarf means that there is a relatively large reflex motion induced by the orbital motion of any planetary companion to the brown dwarf. This is potentially detectable with high resolution, sensitive astrometric observations. In particular, the ACS offers fine spatial resolution and high sensitivity to greatly improve the effectiveness of observations of this type.

Secondly, the small size of the brown dwarf means that it is particularly responsive to photometric occultations by small planetary bodies. For example, an *Earth* sized planet at the Roche limit would give a potentially measurable 1% photometric drop in flux from the brown dwarf during an occultation. The high ACS sensitivity means that shorter integration times are required and hence better time resolution across an occultation.

Of course feasibility depends on there being planets in cooperative orbits to induce these perturbations, however if they do exist, then it may be shown that with a modest allocation of orbits (of order 10 to 20) detection is eminently possible. An existing program to use the WFPC-2 to make similar measurements exists and is currently running on HST, with program principal investigator C. Burrows.

3. Summary

To summarize, if Nature chooses to offer us suitable targets, then planet detection is close to the edge of what will be feasible with the Advanced Camera for Surveys on board the Hubble Space Telescope. Specifically, we anticipate attempting to detect planets directly, comparable in size to Jupiter around α Centauri using the coronagraphic capability of the Advanced Camera. Also, a series of observations will be made of the brown dwarf Gl 229B in order to seek astrometric reflex motion and photometric occultation events that could probe planet masses substantially less than that of Jupiter. If the observing circumstances are favorable and the instrument performs to expectation, then we may for the first time find planets using direct imaging, and less directly, planets of low mass.

References

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- Ford, H.C., et al. 1996, SPIE, 2807, 184.
- Wiegert, P.A. & Holman, M.J., 1997, AJ, 113, 1445.