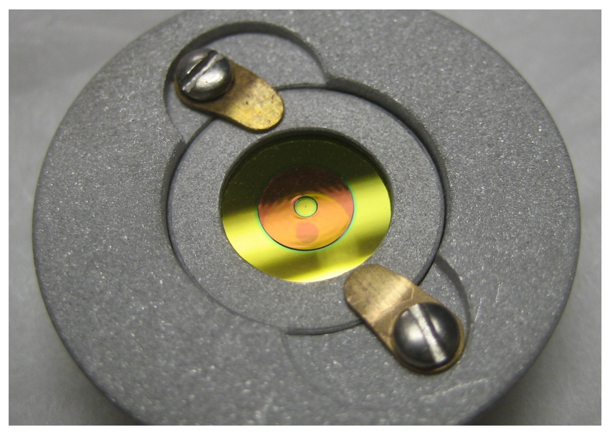

# Smoothing out the wrinkles: on-sky testing of the Apodized Phase Plate at 5 microns

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## Introduction

The direct detection of extrasolar planets requires high angular resolution combined with high contrast imaging techniques. Coronagraphs and pupil transmission apodization provide two methods for suppressing diffraction **but at a significant cost in throughput and angular resolution**. We present the first implementation and on-sky tests[1] of an Apodized Phase Plate (APP), which suppresses diffraction at a modest cost in detection sensitivity.

## Principle of the APP

A plane wavefront of wavelength $\lambda$ incident on a telescope aperture diameter D forms an image that consists of a disk containing the bulk of the incident energy (the core) and a static diffraction pattern surrounding this core (the halo).

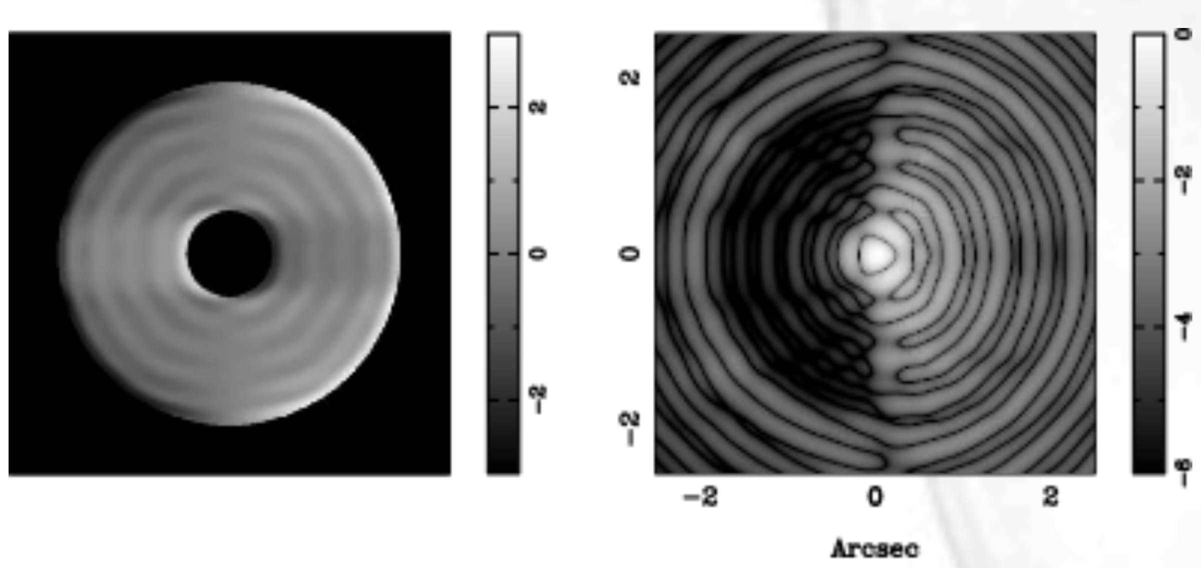


Fig. 1 The APP design (scale in microns) and the resultant PSF covering 6 decades. APP Strehl is 69%.

The APP introduces a specific wavefront aberration at an intermediate pupil plane within an imaging camera[2]. The effect of this wavefront is to suppress diffraction in the halo.

Small amplitude ($h \ll \lambda$) sinusoidal ripples are added in the pupil plane, generating two "speckles" on either side of the image core. The ripple geometry is adjusted to make one speckle cancel out a $2\lambda/D$ region of the diffraction halo. Additional ripples are iteratively added in the pupil plane to suppress diffraction over a given region - see Figure 1. The rotationally non-symmetric figure is cut into a zinc selenide plate using diamond turning techniques.

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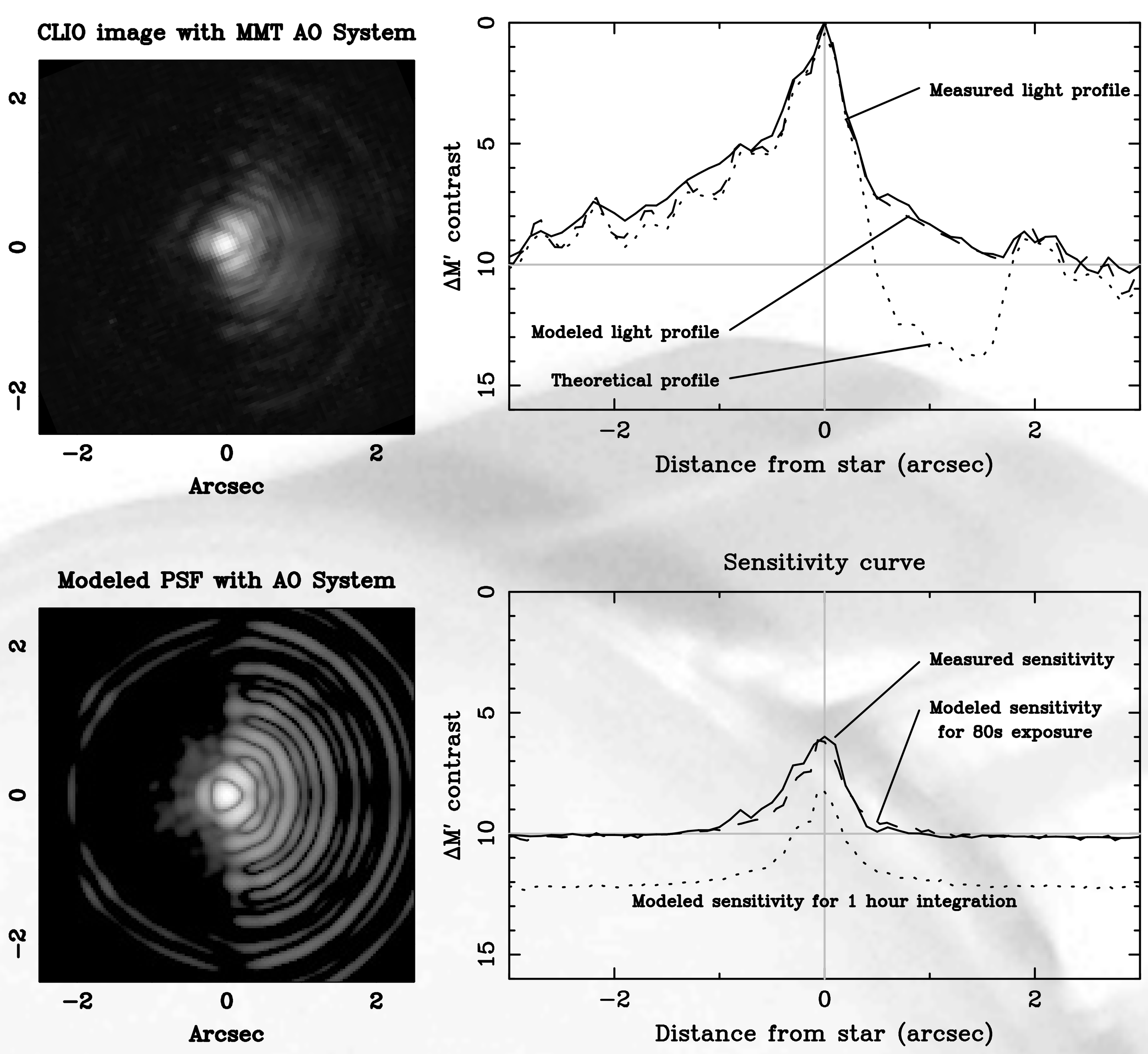


Fig. 2 (left) Measured and modeled APP PSF. (right) The radial light profile averaged over a 150 degrees wedge. The dashed lines are the AO modeled fits. Sensitivity curves are $1\sigma$ limits.

## Observations and Modeling

Our engineering data consists of 16 coadded 5 second exposures of a M'=3 nearby star equalling a total on-sky integration of 80 seconds with the Clio camera[3] at M' band ($\lambda$=4.85μm). The camera is fed by the MMTO NGS AO system, which uses a deformable secondary mirror. The plate is designed for observations at thermal wavelengths, where theoretical models indicate a favourable contrast ratio for young exoplanets[4].

The resultant image (Fig 2) shows that the plate suppresses diffraction from 2 to $9\lambda/D$ as specified. We modeled the MMT AO system with 56 Zernike modes of correction and with servo lag error. The atmosphere is modeled as the sum of two independent phase screens moving at right angles to each other, both with a Kolmogorov-Taylor power spectrum. The data is fit with a Fried length of 20cm (at 500nm), a mean wind velocity of 4.8 ms$^{-1}$ and a measured Strehl of 86%.

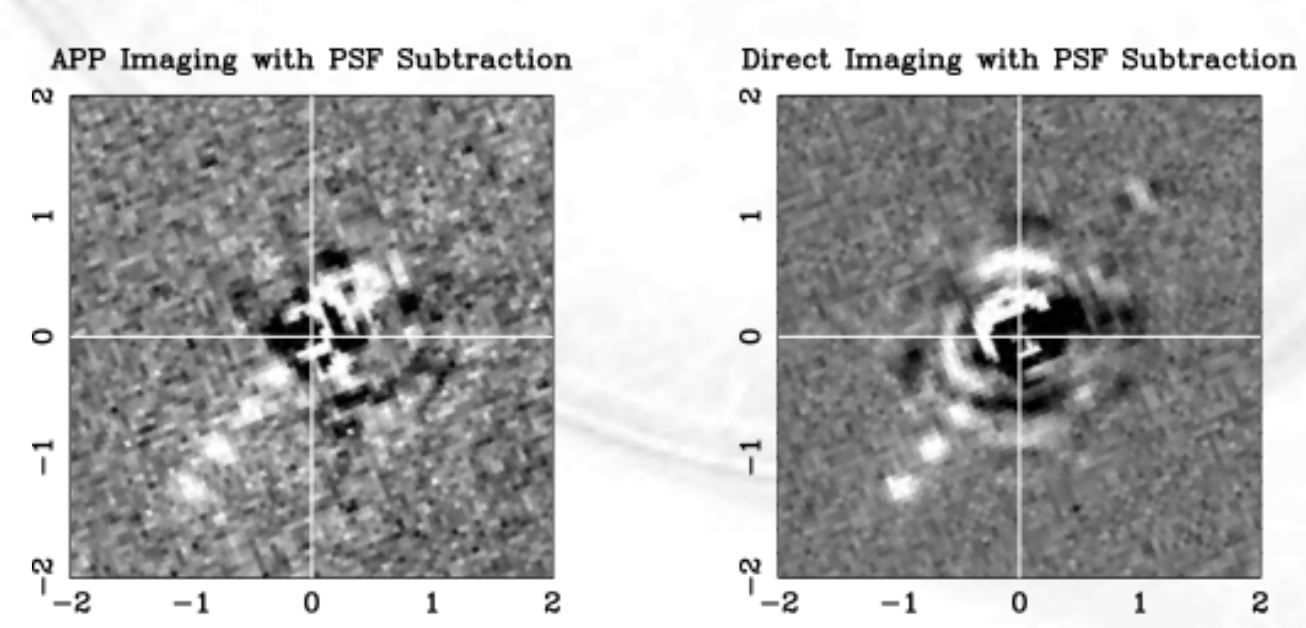


Fig. 3 Comparing PSF subtraction for direct and APP imaging. The four fake planets are 7.5 mag dimmer than the primary star. Intensities are scaled so that planets have equal brightness. The innermost planet is lost in the diffraction halo noise residuals for direct imaging, but it is clearly seen when the APP is used.

For the first time in a high Strehl system, the APP has suppressed diffraction to reveal the wind driven servo lag halo, which follows a predicted minus five thirds power law[5].

Assuming no other noise contributions to the halo for longer exposures, we predict a $5\sigma$ sensitivity limit of $\Delta M'$=10.2 magnitudes at $2\lambda/D$ (0.38 arcsec) for a 1 hour exposure.

## Conclusions

We have demonstrated the APP technique at thermal wavlengths. The APP suppresses diffraction below the AO system errors, enhancing planet detection at small radii (see Figure 3). Further experiments this Fall will determine if we can reach the estimated sensitivity limits with longer exposures.

### Why look for planets at M band?

- High Strehl ratio
- Young exo-Jupiters have good contrast
- Thermally clean and simple science light path with adaptive secondary mirror AO system

## References

[1] Kenworthy et al. 2006, ApJ, submitted

[2] Codona & Angel 2004, ApJL 604, 117

[3] Sivanandam et al. 2006, SPIE 6269

[4] Burrows, Sudarsky & Lunine 2003, ApJ 596, 587

[5] Angel 2003, ASP Conf. Ser. 294, 543

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