High Contrast Imaging of Extrasolar Planets

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Abstract. Gaussian aperture pupil masks (GAPMs) can in theory achieve the contrast requisite for directly imaging an extrasolar planet. We use lab tests and simulations to further study their possible place as a high contrast imaging technique. We present lab comparisons with traditional Lyot coronagraphs and simulations of GAPMs and other high contrast imaging techniques on HST.

1. Introduction

The search to directly image an extrasolar planet requires contrast levels of \( \sim 10^{-9} \) a few \( \lambda/D \) from the central star. Scattered light in a telescope and the diffraction pattern of the telescope’s aperture limit the contrast possible for direct detection of faint companions. The circular aperture of telescopes creates a sub-optimal diffraction pattern, the so-called Airy Pattern which is azimuthally symmetric. In addition, the intensity in the diffraction pattern of the circular aperture declines as \( \theta^{-3}/\theta_o \), where \( \theta_o = \lambda/D \). Currently the best way to diminish the Airy pattern is to use a coronagraph by using the combination of a stop in the focal plane that rejects a majority of the central bright object’s light and a Lyot stop in the pupil plane to reject high frequency light (Lyot 1939; Malbet 1996; Sivaramakrishnan et al. 2001). Several recent ideas explore the use of alternative “apodized” apertures for high contrast imaging in the optical or near-infrared (Nisenson & Papaliolios 2001; Spergel 2002; Debes, Ge, & Chakraborty 2002). These designs revisit concepts first experimented with in the field of optics (Jacquinot & Roizen-Dossier 1964). Other designs, such as the band limited mask, seek to null the light from a central star in much the same way that a nulling interferometer performs (Kuchner & Traub 2002).

By placing a mask into the pupil plane with a gaussian aperture, one can transform a traditional circular aperture telescope into one with a diffraction pattern better suited for high contrast imaging. Using a mask represents a quick, efficient, and cheap way to test this emerging imaging method to determine its advantages and tradeoffs and compare them to the performance of other existing techniques. Preliminary results of observation with a prototype gaussian pupil mask can be found in Debes et al. (2002).

In this proceeding we report further lab tests of the performance of GAPMs compared to lyot coronagraphs with similar throughput as well as testing the new technique of combining a GAPM with a coronagraphic image plane mask.
We theoretically compare different techniques with the same throughput on the Hubble Space Telescope to determine what may be useful in a real spacecraft.

2. Equal Throughput Comparisons

A fairer comparison between a Lyot coronagraph and the GAPM is to have equal throughput designs and compare their contrast levels. As part of lab experiments that we are performing we compared two new GAPM designs with a Lyot coronograph that had a comparable throughput. Two types of designs were tested, idealized apertures with no secondary structure (20% throughput) and realistic masks that will be used for future observing (30% throughput), which have two gaussian aperture per quadrant, avoiding support structure. Un saturated images GAPMs were taken to predict the flux for the longer, saturated images. We took exposures that had on the order of $10^7$ counts in order to image the PSF. We found that this was insufficient to get high S/N on the fainter portions of the PSF and we estimate that beyond 1-2″ the read noise begins to dominate. Longer integrations are planned.

For the coronagraphic modes we used a gaussian transmission focal plane mask with a FWHM of 500µm ($\sim 11\lambda/D$). Short exposures were taken without the mask for estimating the peak flux of an unblocked point source for a given exposure time. The mask was then carefully aligned to within 1 pixel to block the point source.

Figure 1 shows the results of these lab tests. In both cases the hybrid designs perform as well or better, both reaching $\sim 2 \times 10^{-6}$. The flattening of the profile suggests that the observations were hitting the read noise limit of the PICNIC detector on PIRIS. Other experiments that were done where the mask was misaligned by several pixels presented dramatically worse results, underscoring the need for subpixel alignment and stability over an observation. This points to the utility of the GAPMs alone for quick surveys and hybrid or Lyot designs for deeper searches.
3. Testing other types of masks

Given the large number of potential ideas for high contrast imaging, and due to a lack of many lab tests of these designs, a way to model some of the various contrast degradations present in a real space mission would be useful for determining what designs are better suited for future TPF type missions. A strong test would be to compare the performance of the different designs on the HST, where many of these different errors are well modeled. Tinytim, the PSF modeling software used by the Space Telescope Institute, has accurate wavefront error maps of the telescope (Krist 1995). Using these wavefront error maps as input to our models allows us to compare all of the different designs with an equal footing of throughput.

Figure 2 shows a horizontal cut along the axis of highest contrast for all of the designs. In this preliminary simulation the band limited mask performs slightly better than the other designs for the same amount of throughput. This is because the Lyot stop for the band limited mask is undersized from its optimal shape by about 10%. This would block some of the residual light that leaks through the focal plane mask. These simulations ignore mask errors in both the focal and pupil planes. Possibly with PSF subtraction techniques a factor of 10-100 deeper contrast could be achieved, allowing some bright extrasolar planets to be observed with HST. Further simulations need to be done to better understand the feasibility of such observations.

4. Conclusions

We have performed several simulations, lab tests, and telescope observations with GAPMs and Lyot coronagraphs in order to better understand the interplay between theory and the reality of observations. GAPMs alone provide an improvement over a simple circular aperture for quick high contrast imaging. The combination of a GAPM and a coronagraphic mask further suppresses and improves the performance of the GAPM alone. The masks are very sensitive to an accurate reproduction of shape and thus need accuracies that may be as restrictive as sub-micron precision. This is possible with new nanofabrication techniques that have been perfected at the Penn State Nanofabrication facility, where future masks may be produced. Precisely fabricating these masks can potentially improve performance to the ideal limit for a mask provided it is above the scattered light limit of the telescope, bringing it in line with Lyot coronagraphs of comparable throughput. Simulations of different techniques on the HST provide an avenue to test new technologies for future NASA missions such as TPF, and show what can be possible from space.

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Figure 2. Horizontal cuts of the PSFs that would be generated on HST at .9 µm for various designs postulated as useful for extrasolar planet detection.

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