Coronagraphy computer practicum

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December 8, 2010

Coronagraphy is an astronomical technique that enables the detection of faint structure very close to an extremely bright source. “High-contrast imaging” is a better term, but many coronagraphic tricks used at modern telescopes can be traced back to the work of Lyot in the 1930s, who first succeeded in imaging structures in the solar corona close to the solar limb, without the need for a solar eclipse. Modern coronagraphy is mostly geared towards imaging of circumstellar disks and extrasolar planetary systems. The ultimate goal is the direct detection of extrasolar planets and their spectroscopic characterization. The challenges for coronagraphy are twofold. The dynamic range between the photon flux from an exoplanet and the flux from the parent star is huge; up to 10 orders of magnitude. The first goal of coronagraphy is therefore to reduce the ‘glare’ from the starlight at an early stage in the optical train, such that the detector does not get saturated, and stray light and diffraction issues cannot create a halo of starlight that is still orders of magnitudes brighter than the real circumstellar structure. Secondly, the angular separation between star and planets is small, so often a coronagraphic instrument is designed to furnish a PSF with a very steep drop-off in intensity within a few angular resolution elements (λ/D, with D the telescope diameter).

Within this practicum, you will explore several tricks used in coronagraphic systems used for high-contrast imaging of exoplanetary systems. You will simulate the effects of various optical elements within a simulator that you will program yourself. You are free to choose the programming language, but we recommend a package that is meant to deal with image data, like IDL. We also advise you to first read through all assignments and then try to create a fairly generic program that can be used throughout this practicum by merely changing some input parameters. Parts in *italic* are not mandatory, but still extremely interesting...

1. Create a pixelated model of an unobstructed, circular entrance pupil of a telescope. Let the diameter be 201 pixels, which corresponds to a 10-m telescope. Append 2×300 dark pixels around it (so use an array of 801×801), for reasons that will become clear later. Assume for now that the illumination is uniform and that there is no wavefront error. Why do you need to use complex numbers in your array?

2. Compute the PSF that your telescope delivers in its first focus. Make images for amplitude, phase and intensity (i.e. photon flux). Explain the structure you see in the PSF. Why did you need to append dark pixels around the pupil? What is the pixel scale in arcseconds for $\lambda = 600$ nm? Make a logarithmic contrast plot for a representative cross-section of this PSF: stellar photon flux vs. λ/D. Scale all future plots to the center of the non-coronagraphic PSF, which then becomes 1 by definition.

3. Apply a completely opaque coronagraphic mask in the first focal plane. Make the radius of this circular mask 2 λ/D. Examine what happens in a second pupil plane and a second image plane. Think carefully about how and when to unscramble your images before you apply Fourier transforms. Where does most of the diffracted light at the coronagraphic focal plane mask go in the second pupil? Why do you see rings in this pupil? Apply a “Lyot stop” to take out

this diffracted light. How large does this mask need to be? How much useful light does it then block? Correct for this fraction of light in all future plots. What does this change to the typical diffraction-limited size λ/D? What would be the shape of the Lyot mask if there would be an obstruction at the entrance pupil, cause by a secondary mirrors and the “spiders” that support it? Make a contrast plot for the second focal plane and compare it with the non-coronagraphic contrast plot (in intensity, not amplitude). What happens to the strength of the diffraction rings? *Also, make plots for masks of different sizes (1 λ/D, 4 λ/D). Should you use Lyot stops of different sizes then?*

At this point you have simulated a complete optical system. All following exercises can be completed by modifying the amplitude or phase properties of the various components in the optical train.

4. The next goal is to get rid of the Airy rings in the coronagraphic focal plane (that still has a $2\lambda/D$ mask radius), to be able to increase the contrast at a few λ/D. Go back to your first pupil plane and apply an apodization by simulating a mask with variable transmission. What apodization function would you use if you want the first PSF to look more like a Gaussian instead of a Bessel function? *Experiment with the width of the apodization to optimize the contrast at 4 λ/D.* What happens at the second pupil plane before you apply the Lyot stop for an apodization with a typical width of $D/2$? Do you need to apply a Lyot stop? Compare the non-coronagraphic and coronagraphic contrast curve with the ones obtained before. How much useful light do you lose due to the apodization? Correct for this in the plots. What would the apodization look like in case of a central obscuration of the pupil?

5. Up to now, we have assumed that the optics are perfect and that there is no seeing. First, evaluate what happens in case of a tip/tilt error between your telescope and the coronagraphic mask. Set up the optical system again without apodization and with a $2\lambda/D$ mask plus appropriate Lyot stop. Implement this error as a phase term in the first pupil, with a total phase difference of π from one side of the pupil to the other. How much light starts leaking past your coronagraphic mask? Compare the contrast curves (in the direction of the tip/tilt error). To what translation of the star (in λ/D) does this wavefront error correspond?

6. Next, apply the wavefront error from `AOWFE.dat` (courtesy: Visa Korkiakoski) that is obtained from an adaptive optics simulation. This file contains 201×201 pixels of unformatted floating point phase data with unit meters for the wavefront error. Why is this wavefront much different from the tip/tilt wavefront? What happens to the PSF? How effective is the coronagraph now compared to the ideal contrast curve? Where does most of the light go, and why? How many actuators of the deformable mirror were set up across the aperture?

7. *Coronagraphic action can also be achieved with just phase manipulation instead of amplitude manipulation. Remove all masks, apodizations and wavefront errors, and implement the apodizing phase mask from `APPphase.dat` (courtesy: Matt Kenworthy) in one of the pupil planes. The phase information is given in radians. The corresponding pupil shape on which the design was based can be found in `APPamp.dat`. What happens in the consecutive image plane? Why does only one half of the image next to the star get cleared out? How in principle could the part on the other side get cleared out as well? How could you implement such a phase mask in reality? What happens if you change the wavelength by 40%?*

8. *Phase tricks can also be applied in the focal plane, without any apodization in the pupil plane. Construct a “four quadrant phase mask” for which two quadrants get a π phase shift. Make the mask rotationally symmetric, given that the PSF is sampled with an odd number of pixels. Make the central single pixel opaque. What happens in the pupil plane? Do you need to apply a Lyot stop? What is the suppression?*

Select the best coronagraphic set-up that you simulated based on a performance criterion that you define. Make a plot that shows this performance compared to the non-coronagraphic PSF.