# Starlight Suppression with Coronagraphs

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Stellar coronagraphs are instruments designed to suppress the veiling glare of starlight so that faint planets can be seen adjacent to their parent stars. The glare is caused by both diffraction (sidelobes) from the aperture boundaries including the outer limit of the pupil, the secondary obscuration, secondary support structures, and mirror segment gaps, and scatter from the imperfect optical surfaces in the telescope and instrument. Generally speaking, coronagraphs are easier to design on filled, off-axis apertures than on segmented, on-axis apertures.

The diffraction problem can be addressed in three ways:

- Pupil Apodization: The first solution is to apodize the pupil. Apodization, like a low-pass electronic filter, reduces sidelobes by cancelling or removing diffracted light from the beam and allowing for the use of a small central obscuration to remove the undiffracted starlight. This is accomplished either by placing a specially designed mask at a pupil image, or by using optics to concentrate the beam in an advantageous way.. Figure 1 shows a gray scale apodization mask function for a segmented aperture telescope, while Figure 2 shows an optical remapping solution. Examples of this strategy include the phase-induced amplitude apodization (PIAA) or the apodized pupil lyot coronagraph (APLC).
- Lyot Mask: The second approach is to use masks in the image plane designed to diffract all the on-axis light to the outer edges of the beam. This is then followed by another mask at the reimaged pupil, called the Lyot plane, to block the outer edges of the beam and remove the diffracted starlight (Figure 3). Off-axis light from a nearby star passes around the first mask and then through the gap in the Lyot stop. Examples of this strategy include the hybrid lyot coronagraph (HLC) and vector vortex coronagraph (VVC).
- Nulling Interferometry: The third solution is to split the pupil light into two beams and then recombine them using a phase shift and beam shear to cancel the on-axis starlight but not off-axis source flux (Figure 4). Examples of this strategy include the visible nulling coronagraph (VNC).

Coronagraph designers for space-based corongraphy are gravitating toward hybrid approaches combining pupil apodization and image plane masking to deal with segmented apertures, but other solutions are still being explored.

With diffracted light eliminated from the system, scattered light originating with aberrations, coating defects, and contamination remains and must be removed. This is achieved by flattening the wavefront using a deformable mirror (DM), with typically > 1000 actuators within the pupil (Figure 5). To control the wavefront, it must first be sensed. This is done by adjusting the DM surface several times while recording the change in image plane illumination. An algorithm then determines the required wavefront correction and commands the DM to form a new surface shape. This is repeated until a "dark hole" is formed with a level of glare low enough to expose a planet. Figure 6 shows a dark hole achieved in the laboratory in a 10% bandpass.

The desired level of suppression is $10^{-10}$ for imaging of an Earth-like planet around a Sun-like star; that is, the residual scatter in the image plane after diffraction and wavefront control is 10 billion times below the level of the incident starlight. Amazingly, this can be achieved using optics of equivalent quality to those currently used on the Hubble Space Telescope, and is limited mainly by the ability to accurately set the DM and to hold the system stable. The stability issue is perhaps the most challenging, with sub-nanometer requirements imposed on the wavefront. This is particularly challenging when it comes to low-order aberrations such as pointing, focus, coma, and astigmatism. To measure and control these terms, low-order wavefront sensors with fast response times using the starlight rejected by the coronagraphic masks are being developed.

The effectiveness of a coronagraph is evaluated based on several performance metrics: the inner working angle (IWA; i.e. how close to the star you can observe), bandwidth over which it can operate effectively, the throughput of the system, and the raw contrast (i.e. the level of glare suppression). Typically, achieving high performance at small IWA leads to either lower system throughput or increased sensitivity to aberrations and the finite stellar diameter. The challenge of suppression increases with optical bandwidth; the broader the band (more signal photons), the more background appears, the lower the raw contrast achieved, and the more challenging the wavefront sensing and control becomes. Perhaps most importantly, the IWA scales proportionally with wavelength – the same coronagraph that works at 50 milli-arcsec (mas) at a wavelength of 500 nm will be limited to about 100 mas at 1 μm. This is an important factor when characterizing exoplanet spectra in the near IR.

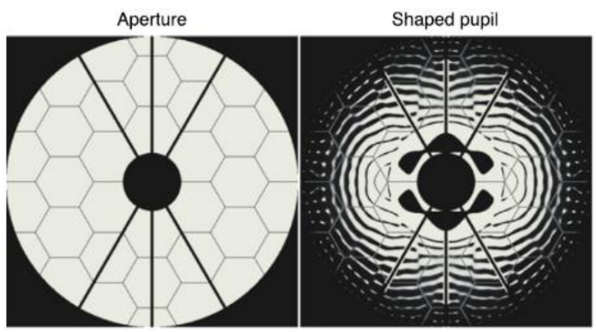


**Figure 1:** Pupil apodization on a segmented aperture. N'diaye *et al.,* ApJ 818:163 (2016).

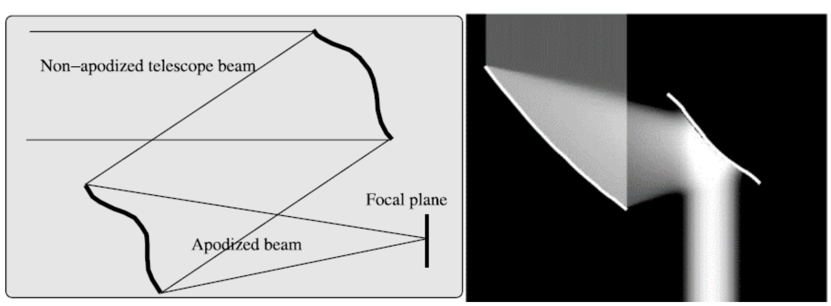


**Figure 2:** Pupil remapping. Guyon *et al.*, ApJ 622:744 (2005).

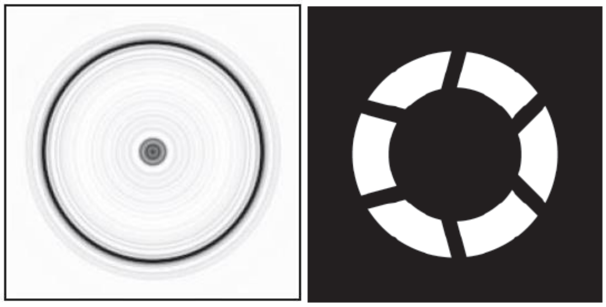

**Figure 3**: Hybrid Lyot image plane mask (left) and Lyot mask (right) for the WFIRST coronagraph. Trauger *et al.*, Proc. SPIE 8864, 886412 (2013).

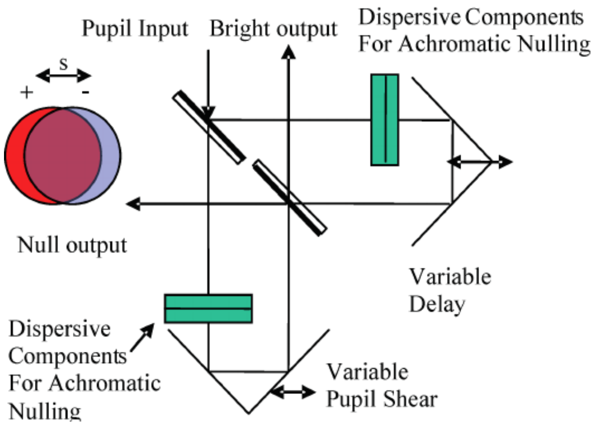


**Figure 4**: Nulling coronagraph. Shao *et al.*, Proc SPIE 6265, 626517 (2006).

**Figure 5**: 64 x 64 element DM with a fused silica facesheet. Trauger *et al.*, Proc. SPIE 8151, 81510G (2011).

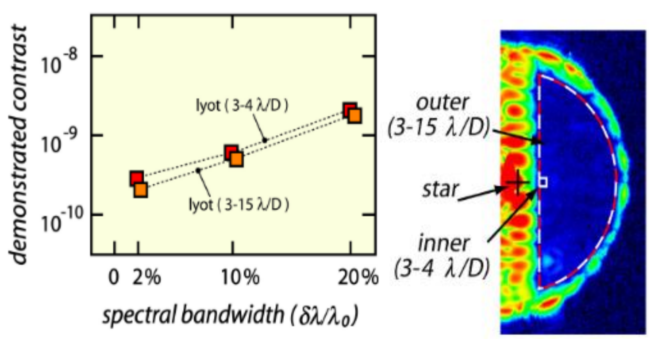


**Figure 6**: Dark hole in broadband light, demonstrated at the JPL High Contrast Imaging Testbed. Trauger *et al.*, Proc. SPIE 8151, 81510G