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The potential of high-contrast coronagraphy

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Abstract. The direct detection of faint companions near much brighter stars requires the development of very high-contrast, small field-of-view detection techniques, and the past decade has seen remarkable conceptual and instrumental progress in this area. New coronagraphic techniques are being developed and deployed, as are extreme adaptive optics (ExAO) systems that will enable the advantageous exploitation of these new techniques. This paper provides a short overview of promising high contrast coronagraphic techniques, as well as recent examples of ExAO coronagraphy and transit measurements obtained with the ExAO-level "well-corrected subaperture" at Palomar.

1. Introduction

As is discussed in this volume, rapid progress is being made in the search for planets around nearby stars. Radial velocity (RV) measurements have led to the detection of hundreds of exoplanets, and transit measurements are beginning to add significantly to the tally. Indeed, transit measurements have also enabled spectroscopic measurements of select exoplanets. While these techniques will no doubt provide ever increasing observational data, a technique which is only recently starting to come into its own is the direct imaging of exoplanets. Indeed, the recent companion detections discussed in this volume highlight both the promise and the difficulty of direct imaging. The ultimate goal of course is the ability to directly image nearby solar systems, so as to allow both direct observations of orbital motions and phases, as well as spectroscopic measurements of each of the exoplanets. Direct imaging has a further advantage in that it can potentially access a region of parameter space complementary to those accessible to the RV and transit techniques, since it is particularly sensitive to companions at large separation, i.e., those with long orbital periods.

The main obstacles to the direct imaging of nearby exoplanets are their very low brightness ratios (or contrasts) relative to their host stars, combined with their small separations. In reflected light, an exact terrestrial planetary analog located 1 AU from a G2 star would be only slightly more than 10^{-10} as bright as the star. Because of its larger diameter, a jovian planet at the same orbital radius would be roughly a factor of 100 brighter. Since reflected light decreases as r^{-2}, a measurement capability at either a smaller inner working angle (IWA), or a deeper contrast, c, would be beneficial for detecting exoplanets in reflected light, as either would expand the size of the accessible search space (inward and downward, respectively). Note that because of this r^{-2} brightness dependence, the IWA and attainable contrast, c, can be traded off against each other, i.e.,

Table 1. Coronagraphic Alternatives

	Pupil Plane	Focal Plane
Amplitude:	Amplitude apodization Shaped pupil Pupil remapping External Occulter	Hard-edged mask Graded-intensity mask Band-limited mask
Phase:	Pupil phase apodization	Circular phase mask Four quadrant phase mask Scalar vortex mask Vector vortex mask

a system with a smaller IWA can have a more modest contrast capability. One could thus combine these two quantities into a figure of merit reflecting the rough size and depth of the (inner edge of the) accessible search area. For example, one could define a "coronagraphic area", as A = c * IWA^2 (with the units of angular area.) The reason for such a definition is that the A needed for detection of a given type of exoplanet at a given distance from us is a constant, independent of the star-planet separation. Moreover, A also gives the maximum distance to which such an exoplanet can be detected with a given coronagraph.

Young jovian planets also contribute their own emitted light in the near-IR, which is independent of distance from the star, allowing for much easier detection possibilities, potentially to about the 10^{-4} level. At the current time, attainable contrasts at very small angles are limited to $\sim 10^{-4}$ or so also, enough to motivate initial searches with existing capabilities. However, both coronagraphic and wavefront sensing and control techniques have been undergoing significant advances recently, leading to expectations of significantly improved performance with next generation ExAO systems to come on line in the near future. This paper summarizes promising techniques for high-contrast coronagraphy, focusing on physical principles, and concludes with recent examples of initial coronagraphy and exoplanet transit measurements made with an existing ExAO system. Space limitations prevent addressing fully all of the exciting developments in these fields.

2. High-contrast Coronagraphy

Coronagraphy began with the solar coronagraph of Lyot (1938), which blocked the sunlight collected by a single telescope aperture while allowing transmission of light from the off-axis coronal light. In the intervening years, and especially in the past decade, a number of quite novel and promising alternatives for stellar coronagraphs have emerged. Coronagraphic approaches to starlight suppression still rely on the modification of the incoming stellar electric field distribution prior to the generation of the final focal plane image, but potential modifications may be applied either in a pupil plane or a focal plane, and either to the amplitude or the phase of the field. A number of potential coronagraphic alternatives are summarized in Table 1, based on this fourfold characterization.

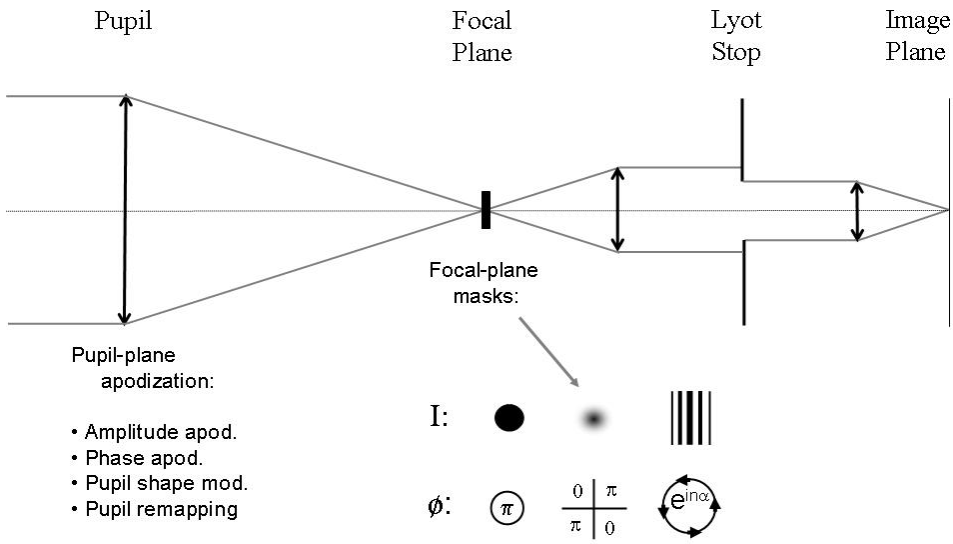

Figure 1. Schematic coronagraph layout, with pupil and focal plane modifications indicated. Possible focal plane masks include: First row: hard edged blocker, graded attenuator and band-limited mask. Second row: circular phase mask, four-quadrant phase mask and vortex mask.

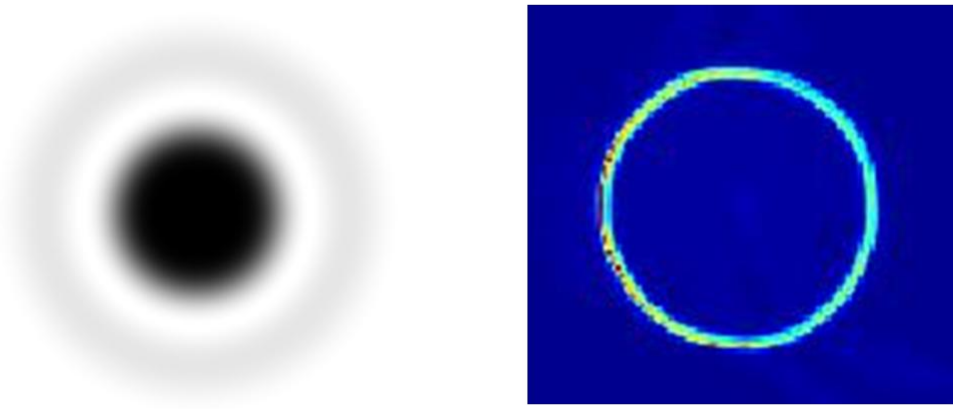

Figure 2. Measured ring-like pupil (right) generated with a band-limited mask (left) manufactured at JPL, as per Krist et al. (2007). An undersized Lyot stop can then easily reject the light in the ring-like pupil.

For reference, a conceptual layout of a general coronagraph is shown in Fig. 1. Guyon et al. (2006) compared the imaging properties of the coronagraph alternatives known at the time, and based on the metric of "useful throughput", found that pupil remapping and vortex phase mask coronagraphy (see below) are closest to ideal coronagraphic performance. Several of the promising coronagraphic alternatives are now briefly discussed.

A classical amplitude-based Lyot coronagraph rejects starlight using two blockers. First, a small opaque mask several λ/D in diameter is centered on the focal plane stellar image, in order to block the innermost part of the point spread function (PSF). Only the high frequency components of the PSF then propagate to a subsequent pupil plane, where they appear localized near the pupil periphery. An opaque undersized pupil stop (the Lyot stop) is then used to further reduce the residual starlight (Fig. 1; see also Sivaramakrishnan et al. 2001).

Because of the Fourier transform relationship between the focal plane and the pupil plane, a hard-edged focal plane stop wil lead to ringing in the pupil plane, so that the light distribution in the subsequent Lyot plane will not be sharply confined near the edge of the pupil. There will thus be significant leakage of starlight into the pupil. Luckily, this ringing can be decreased by using a focal plane stop with a tapered absorption. In the ideal band-limited case (Kuchner & Traub 2002), very high stellar rejection can be provided by the Lyot stop. Fig.

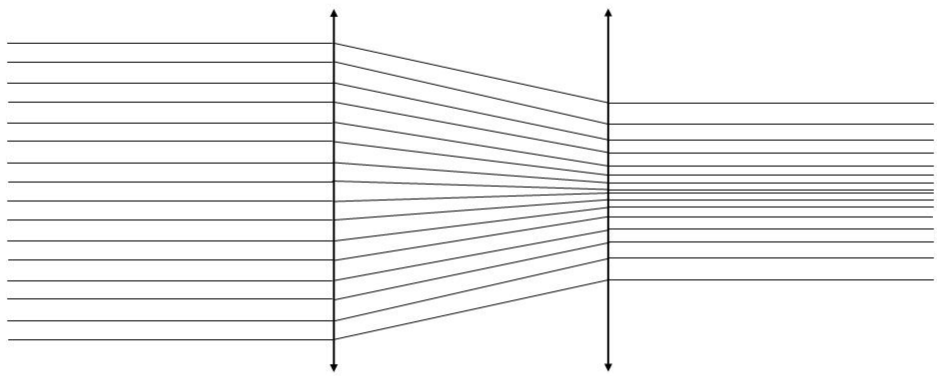

Figure 3. Schematic illustrating the redistribution of light in the pupil in the PIAA approach, described in Guyon (2003).

2 shows an example of the very well-defined ring-like pupil plane distribution recently measured in our lab for a prototype band-limited mask intended for possible use in the JWST NIRCAM (Krist et al. 2007). In the laboratory, focal plane coronagraphy with band-limited masks have demonstrated narrowband contrasts of several 10^{-10} (Trauger and Traub 2007), close to that required for terrestrial exoplanet detection, and work on broadening the passband is also proceeding.

On the other hand, the pupil plane amplitude distribution can also be modified, as in classical apodization. The goal is then to smoothly taper the pupil plane field, leading, after Fourier transformation, to a focal plane spot well-localized near the optical axis, so that little starlight leaks to large angles. One way to effect such an apodization is with a spatially variable pupil plane attenuator. Optimized apodization solutions have been found (e.g. Kasdin et al. 2003), aiming at e.g., the smallest inner working angle (IWA), or at generating a deep "dark hole" search region near the optical axis (Gonzalves & Nisenson 2003). Note that most of the high-contrast coronagraphs planned to come on line on the ground and in space (e.g. JWST) in the next few years include a variation of a classical amplitude-based Lyot coronagraph.

Alternatively, the shape of the pupil can also be modified, so as to provide a focal plane image with localized dark search regions. The simplest pupil shape modification is a square aperture, which is known to have low diffraction along the PSF diagonals (Nisenson & Papaliolios 2001), and more complex pupil

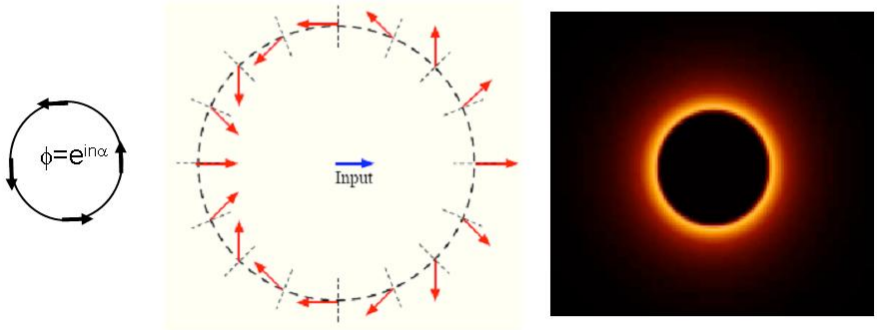

Figure 4. Illustration of the operation of vector vortex coronagraph (Mawet et al. 2008), which uses an azimuthally varying halfwave plate to induce an azimuthal phase variation (left) in the focal plane. The optical axis rotates with azimuth, and the output polarization rotates twice as fast (center). The fast axis orientations are shown as light dashed lines, while the output field orientation, for the input polarization shown, is given by the arrows. Right: the ideal pupil plane distribution after passage through a vortex mask.

shapes also can scatter light preferentially in certain directions or areas, leaving other search regions dark (Kasdin et al. 2003).

However, while intensity apodization does reduce the PSF wings, this generally comes at the cost of lower throughput, because of the loss of pupil area. On the other hand, beam shaping can also be used to alter the transverse beam profile. In the context of coronagraphy, this is referred to as "phase-induced amplitude apodization" (PIAA) (Guyon 2003) or pupil remapping (Traub & Vanderbei 2003). In effect, the pupil is laterally remapped (distorted) to provide the desired tapered distribution. Conceptually, by spreading the outer rays further and further apart (Fig. 3), the incident flat-topped beam is converted to a tapered beam profile (Guyon 2003). Because the PIAA does not rely on attenuation to produce the tapered distribution, it is potentially highly efficient, and can be used to observe quite close to the axis.

For space-based applications, one could also block the starlight by means of an external occulter located well upstream of the telescope (Cash 2006). The occulter must be far enough in front of the telescope to allow planetary light arriving at small off-axis angles to pass by unobstructed, which leads to very large reconfiguration motions when changing targets.

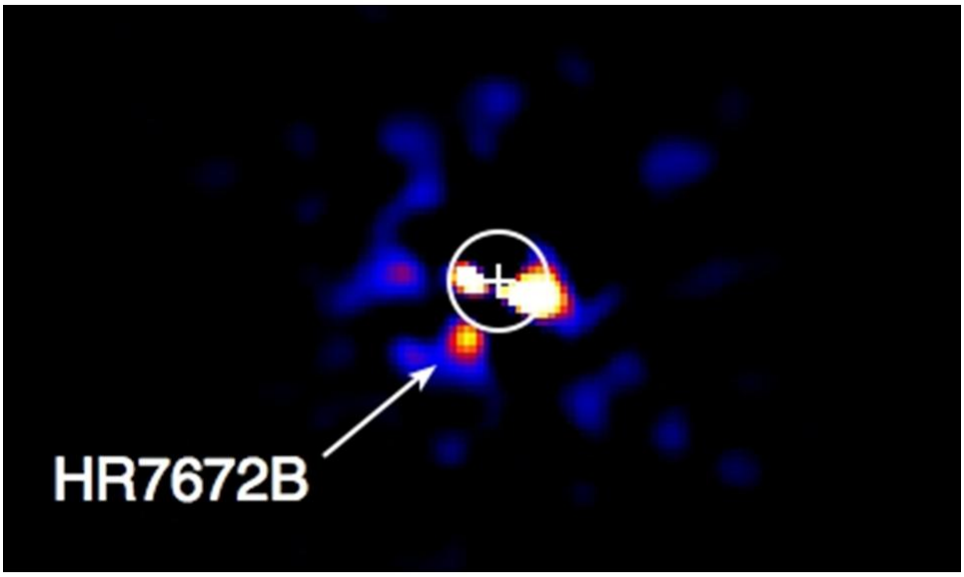

Figure 5. Image of the brown dwarf companion HR7672B obtained with the 1.6 m Palomar WCS. The circle has a radius of 2 λ/D.

On the other hand, the phase of the field can also be modified, and three potential focal plane modifications are illustrated in Fig. 1. The four-quadrant phase mask coronagraph applies alternating phase shifts of π radians in the four quadrants of the focal plane, and so avoids lateral size-related chromaticities (Rouan et al. 2000). This technique has been applied at the VLT (e.g. Boccaletti et al. 2008) and at Palomar (Haguenauer et al. 2006) and will be included in the JWST mid-infrared instrument. Indeed, brown dwarfs as close to the optical axis as 2.8 λ/D have now been detected with phase-mask coronagraphy (Serabyn et al. 2009).

A more recent development is the vortex phase-mask coronagraph, in which an azimuthal phase ramp is applied to the focal plane field. The phase ramp can be generated either by a spatially variable glass thickness (Foo, Palacios & Swartzlander 2005), or polarization-rotation leading to variations in the Pancharatnam phase (Fig. 4; Mawet et al. 2005). The latter approach has maximum search space potential because it has no phase discontinuities except along the optical axis. Such phase-based coronagraphs yield pupil plane distributions in the Lyot plane wherein the starlight lies beyond the original pupil (e.g. Fig. 4). An opaque undersized Lyot stop can then be very effective in removing starlight. Furthermore, because there is no opaque mask present at the center of the focal plane, very small inner working angles can be achieved with phase mask coronagraphy.

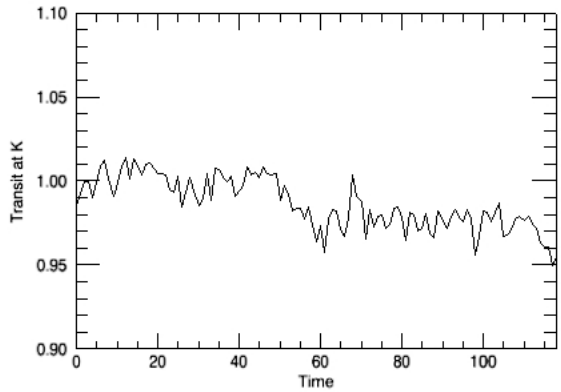

Figure 6. The first half of a primary transit of HD189733 observed with the Palomar WCS in K-band.

On the other hand, the phase of the pupil plane field can also be modified. It is well-known that pupil-plane phase aberrations modify the focal plane distribution. A theoretical treatment of pupil plane phase modification has been provided by Yang et al. (2004), and initial on-sky tests and demonstrations have recently been made (Codona et al. 2006; Serabyn et al. 2007).

3. Recent Progress and Examples

Although ExAO coronagraphic systems do not yet exist on large telescopes, there is one ExAO test facility available already - the ExAO-level "well-corrected subaperture" (WCS) on the Palomar 200-inch telescope (Serabyn et al. 2007). To make up for the WCS's small aperture diameter, a phase mask coronagraph with a small IWA has been employed with it. This system was recently used to image known brown dwarf companions (Serabyn et al. 2009), and Fig. 5 shows an example of a brown dwarf clearly seen at an offset of only 2.8 λ/D. As this image was obtained with an aperture of only 1.6 m, the prospects for future high-contrast imaging on large telescopes equipped with ExAO seem very promising indeed.

Finally, the stability of the PSF provided by an ExAO system brings additional benefits. In particular, the advent of ExaO will also enable a new method of making transit observations from the ground. Fig. 6 shows an example of the first half of a primary transit of HD189733 recently observed with the Palomar WCS. The flux decrease of a couple of percent at the initiation of the transit

is clearly already seen in the raw data. This again indicates a very promising future when ExAO becomes available on large telescopes.

4. Summary

Many approaches to high-contrast coronagraphy have been proposed recently, each with differing strengths and weaknesses in terms of inner working angle, contrast, transmission efficiency, search space, ease of manufacture, etc. A detailed comparison has been provided in Guyon et al. (2006), which points to pupil remapping and vortex phase mask coronagraphy as closest to the ideal case. However, as these are both rather novel approaches, most coronagraphic systems planned for the near future will continue to rely on some variation of an amplitude-based Lyot coronagraph as their starting point. However, very valuable practical experience with several new types of coronagraph is already being gained, both in the laboratory and on existing telescopes.

Next-generation ExAO systems are in the devlopment phase for several ground-based telescopes such as Palomar (Bouchez et al. 2008), Subaru (Hodapp et al. 2008), Gemini (Macintosh et al. 2008), and the VLT (Beuzit et al. 2008), and will include state-of-the-art coronagraphs for exoplanet detection work. New speckle reduction algorithms are also accelerating progress (e.g. Marois et al. 2008), but space limitations prevent a discussion of that topic. Within a few years, the new ExAO coronagraphic systems on large telescopes should thus enable the exploration of a much deeper contrast regime, thereby opening the door to the imaging of ever fainter exoplanets near their host stars.

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