

## IMAGING EXTRASOLAR PLANETS BY STELLAR HALO SUPPRESSION IN SEPARATELY CORRECTED COLOR BANDS

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### ABSTRACT

Extrasolar planets have not been imaged directly with existing ground or space telescopes because they are too faint to be seen against the halo of the nearby bright star. Most techniques being explored to suppress the halo are achromatic, with separate correction of diffraction and wave-front errors. Residual speckle structure may be subtracted by differencing images taken through narrowband filters, but photon noise remains and ultimately limits sensitivity. Here we describe two ways to take advantage of narrow bands to reduce speckle photon flux and to obtain better control of systematic errors. Multiple images are formed in separate color bands of 5%–10% bandwidth and recorded by coronagraphic interferometers equipped with active control of wave-front phase and/or amplitude. In one method, a single deformable pupil mirror is used to actively correct both diffraction and wave-front components of the halo. This yields good diffraction suppression for complex pupil obscuration, with high throughput over half the focal plane. In a second method, the coronagraphic interferometer is used as a second stage after conventional apodization. The halo from uncontrollable residual errors in the pupil mask or wave front is removed by destructive interference made directly at the detector focal plane with an “antihalo,” synthesized by spatial light modulators in the reference arm of the interferometer. In this way very deep suppression may be achieved by control elements with greatly relaxed, and thus achievable, tolerances. In both examples, systematic errors are minimized because the planet imaging cameras themselves also provide the error-sensing data.

*Subject headings:* instrumentation: adaptive optics — planetary systems — stars: imaging — techniques: interferometric

### 1. INTRODUCTION

Optical imaging of extrasolar planets, whether from space or the ground, requires improved methods for halo suppression. These need to work over a broad wavelength band to minimize photon noise in both the wave-front sensor and the planet images. Currently the best-controlled starlight halos are obtained at  $\sim 1.65 \mu\text{m}$  wavelength from both space and ground, with speckle structure at  $\sim 2.5 \times 10^{-4}$  of the star intensity at  $\sim 0''.5$  radius (Schneider 2002; Close et al. 2004). Subtraction methods such as rotation of the *Hubble Space Telescope* (*HST*) and spectral differencing for ground telescopes (Racine et al. 1999) yield a detection limit for faint companions at  $\sim 10^{-5}$  contrast. Order-of-magnitude improvements of these methods may be adequate to image massive young giant planets in wide orbits, but older and less massive giants will generally be much fainter, even when heated by the star. Fainter still will be terrestrial planets, thus an Earth in a twin of the solar system at 10 pc would appear in reflected light at  $\sim 2 \times 10^{-10}$  of the Sun at  $0''.1$  maximum separation. Detection at such faint contrast will likely require new and more powerful techniques, to directly reduce the photon flux (and noise) of the speckle halo, while maintaining exquisite control of systematic errors.

Most proposed optical configurations for deep halo suppression are inherently achromatic, involving a combination of very efficient apodization or coronagraphy (Kasdin et al. 2003; Guyon 2003; Gonsalves & Nisenson 2003) with active correction of wave-front errors (Trauger et al. 2003) and, in some concepts, also of pupil amplitude (Littman et al. 2003). For imaging very close to the star, where terrestrial and old giant planets are likely to be found, the halo component from optical errors is set by lower order terms in the wave-front aberration, and these can be corrected by deformable mirrors of high accuracy but modest spatial resolution (Malbet, Yu, & Shao

1995). However, if wave-front measurements are made across the pupil to determine even low-resolution correction coefficients, they would need to be both finely detailed and highly accurate because any undersampled high-order structure will alias to low order.

This difficulty can be overcome if wave-front and amplitude errors are derived from focal plane measurements. Thus, improved measurement accuracy for phase and amplitude corrections to be applied at the pupil is obtained by phase diversity techniques applied to focal plane images (Malbet et al. 1995; Jefferies et al. 2002). This method was used to measure in detail the *HST* primary mirror aberrations (Roddier & Roddier 1993). All focal plane techniques require the weak halo fluxes to be sensed in limited wavelength bands, and multiple channels will be needed to improve the sensitivity set by photon noise. When rapid corrections are based on wave-front measurements made in the pupil plane, the limit to wave-front accuracy set by photon noise results in a halo with very weak speckles containing just a few photons each (Angel 1994). It can be shown that focal plane measurements of the weak halo speckles themselves can give the same accuracy and level of suppression, provided the same total bandwidth is used (Angel 2003). Focal plane measurements have the advantages that accurate calibration is not needed, because the measurement is null, and non-common-path errors are eliminated if the same detectors are used to provide the deep integrated planet images as well as instantaneous wave-front data. For our application in which the star image must be blocked, it is convenient to derive the errors interferometrically rather than by phase diversity, obtaining the complex amplitude of the weak residual halo with the aid of a reference beam derived from the blocked starlight (Angel 2004).

## 2. HALO SUPPRESSION IN NARROW BANDS

Since multiple wavelength channels are desirable for accurate wave-front sensing, it makes sense to explore the potential for passive and active corrections within each limited bandwidth channel to directly suppress the halo. New modes then become possible, because separate correction of diffraction effects and wave-front errors is no longer required. To implement such schemes, an initial separation of the telescope image into multiple wavelength star images would be made with cascaded dichroic beam splitters or a field grating (Bonnet & Courtès 1962). Labeyrie (2002) has pointed out one approach, in which a conventional coronagraph is followed by a second stage re-imaging device. In it the halo speckle phases are actively modified to be all the same, so at the center of an intermediate quasi pupil their energy is concentrated in a central spot that can be blocked. In our concept for suppression, a coronagraphic interferometer is used to both measure and suppress the halo in a servo loop, as shown schematically in Figure 1. The active elements to control phase and/or amplitude are placed at the pupil image formed in the signal arm or in the reference beam arm to modulate the reference image. One such instrument would be placed at each narrowband star image. In operation at the telescope, the corrections to be applied are determined from measurements of the complex amplitude at each focal plane image pixel, obtained from images recorded before and after phase shifts of  $\pi/2$  in uniform amplitude reference beams.

Multiple instruments, each with two-dimensional arrays of active elements, may at first seem a daunting proposition, but suitable small Micro-Electro-Mechanical System deformable mirrors and liquid-crystal spatial light modulators for intensity and phase control (Littman et al. 2003) are becoming available, as are CCDs with gain for use as fast photon-counting arrays (Mackay et al. 2001). We consider below two new modes of operation. The first is a phase-only alternative to separate apodization and wave-front correction. In the second, conventional apodization and wave-front correction is followed by a second stage in which the residual halo is further reduced by destructive interference.

## 3. METHOD I: PHASE CORRECTION OF BOTH DIFFRACTION HALO AND WAVE-FRONT ERRORS

In this method, the full halo (including diffraction rings) is suppressed not by apodization or Lyot stop but by modulation of phase across the pupil. The basic idea is to superpose Fourier phase components across the pupil that create the complex amplitude at each spot in the focal plane needed to null out the measured value. This is not possible over the whole focal plane, as can be seen from symmetry considerations. Thus the complex amplitude of the diffraction halo is Hermitian, while from pupil phase modulation it is anti-Hermitian, so correction can only be made over half the focal plane. Also, the suppression is more efficient if the outer radius is limited, so we adopt a D-shaped nulled region in the focal plane. The required pupil phase shifts are found by iterative Fourier transform of the complex halo amplitudes measured within the D and are of the order of 1 rad. We envisage that the phase pattern needed to suppress diffraction would be figured permanently on the surface of a deformable mirror and the active control used to clean up residual errors. Phase shifts made by displacement to correct diffraction can be accurate only at one wavelength  $\lambda_0$  and will be systematically off at neighboring wavelengths. For reasonably small changes in wavelength, the relative phase error is given by  $\Delta\phi/\phi = (\lambda - \lambda_0)/\lambda_0$ ; therefore, there will be

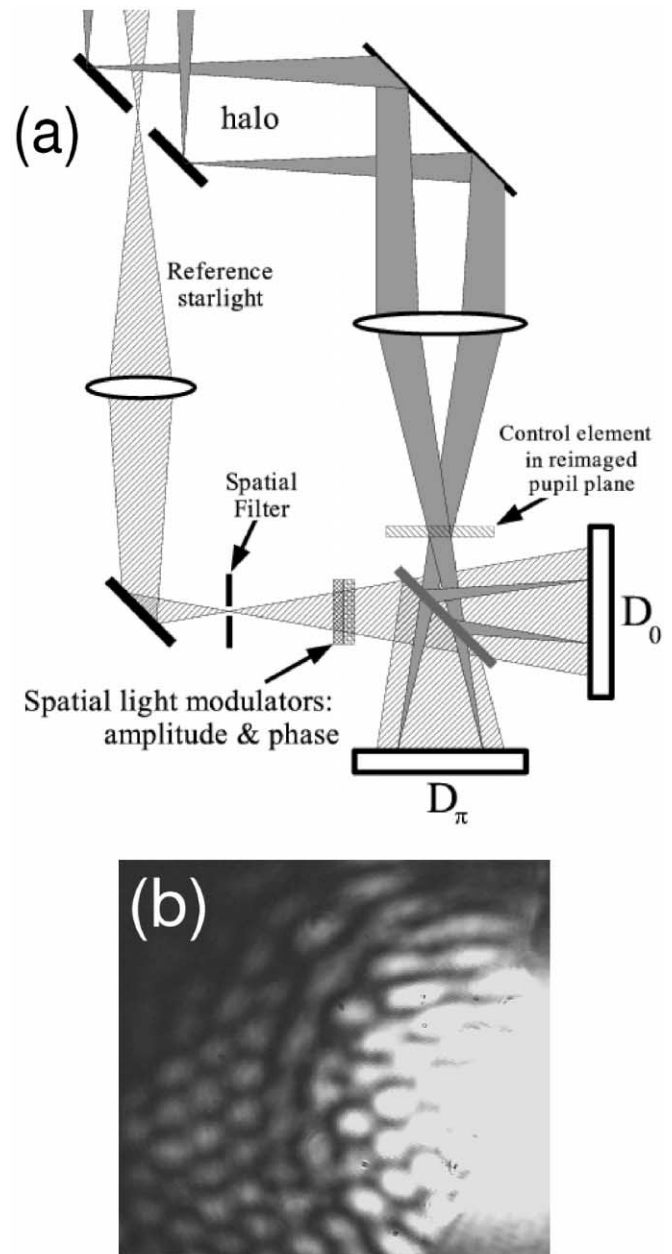


FIG. 1.—Concept for a narrowband coronagraphic interferometer to sense and suppress the stellar halo. (a) A narrowband stellar image enters the system from above. The halo and planet image are reflected from a pierced mirror to be relayed via a pupil stop and beam splitter onto the photon-counting detector arrays marked  $D_0$  and  $D_\pi$ . The diffraction-limited core is passed through the mirror and a spatial filter to be used for phase reference and/or destructive interference of the halo. Active or passive phase and amplitude control elements (e.g., a deformable mirror or spatial light modulator) may be placed in the halo light path at the reimaged pupil (Lyot stop) or in the reference beam. (b) Part of Airy pattern recorded in a lab demonstration, with the reference wave front slightly tilted so that constant phase in the halo would appear as horizontal fringes. The fringe displacement of successive Airy rings reveals the half-wave phase shift between them.

a chromatic increase in the halo intensity that varies as  $[(\lambda - \lambda_0)/\lambda_0]^2$  times the original halo intensity.

As an illustration, we show this method applied to the *HST* in Figure 2. Obscuration of the primary mirror by the secondary and supports results in a complex diffraction pattern. The optimized pupil phase modification yields about 4 orders of magnitude reduction for monochromatic light, with only modest loss of energy (the Strehl ratio is 43%). We have modeled the

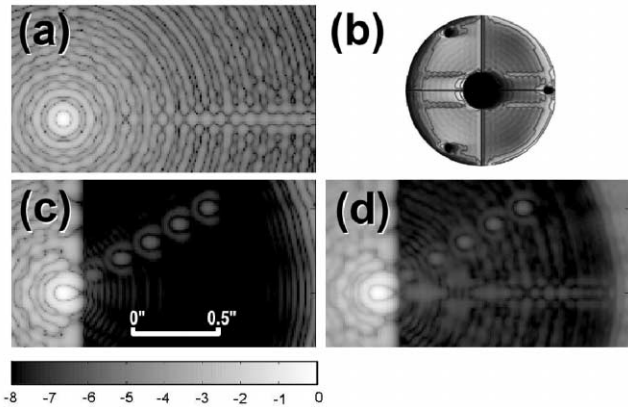


FIG. 2.—Correction of the *HST* diffraction halo by pupil phase adjustment. (a) Diffraction pattern at wavelength  $0.5 \mu\text{m}$  over eight decades, given ideal figure correction. (b) Pupil phase change required to correct for diffraction, optimized for field radius  $2.5\text{--}3.5 \lambda/D$ . The contour interval is  $\pi/4$ . (c) Monochromatic point-spread function (PSF) after correction. Companions at  $10^{-6}$  star are revealed at radial separations in  $0.2$ . (d) PSF at spectral bandwidth of  $10\%$ .

reduced halo suppression for finite bandwidth of  $10\%$ . The contrast at radius  $3.5\lambda/D$  ( $0.15$  at  $\lambda = 0.5 \mu\text{m}$ ) averaged over the band is  $3 \times 10^{-7}$ , still 3000 times below the uncorrected diffraction level.

Such deep suppression and good throughput close to the star compares favorably with conventional coronagraphy. *HST*'s Near-Infrared and Multi-Object Spectrometer coronagraph with a hard field stop of radius  $2.1 \lambda/D$  allows detection of companions as close as  $2.6\text{--}3.7 \lambda/D$  but with suppression of only  $2.5 \times 10^{-4}$  (Schneider 2002). A more aggressive coronagraph for *HST*, including optimized correction of low-order optical errors, could yield strong suppression of  $3 \times 10^{-8}$  but at larger radius ( $7.5 \lambda/D$ ) and with only  $18\%$  planet transmission (Malbet et al. 1994, 1995). A valuable aspect of the new method is that its deep suppression of diffraction and scattered halo can be maintained by adjustments with deformable mirrors alone, avoiding the reliance of conventional coronagraphs on precise manufacture and placement of a pupil mask. It will be particularly powerful for complex or obstructed pupils for which apodization and Lyot stop methods are not very efficient (Sabatke et al. 2004). For example, it could be used to correct the halos caused by gaps and phase steps at the segment boundaries of the *James Webb Space Telescope* and the Keck telescope.

#### 4. METHOD II: ACTIVE HALO NULLING

For deepest suppression over the full annular aperture, apodization would be combined with a second operational mode that we now describe. The idea is to suppress the residual halo directly, by destructive interference in the focal plane. For this mode, the interferometer of Figure 1 would be configured as a coronagraph, with halo suppression achieved in the first instance by apodization preceding the interferometer. On the basis of a Fourier transform of the star halo's measured complex amplitude, the deformable mirror at the Lyot stop within the coronagraphic interferometer would be adjusted to reduce the halo from phase errors. Some faint speckles will remain because of limits to the manufacturing accuracy of the field and Lyot stops and in the setting of the phase correction device. Their complex amplitudes would be remeasured, and the reference beam would be modulated to create a corresponding "antihalo" with the same amplitudes but opposite phases. Destructive in-

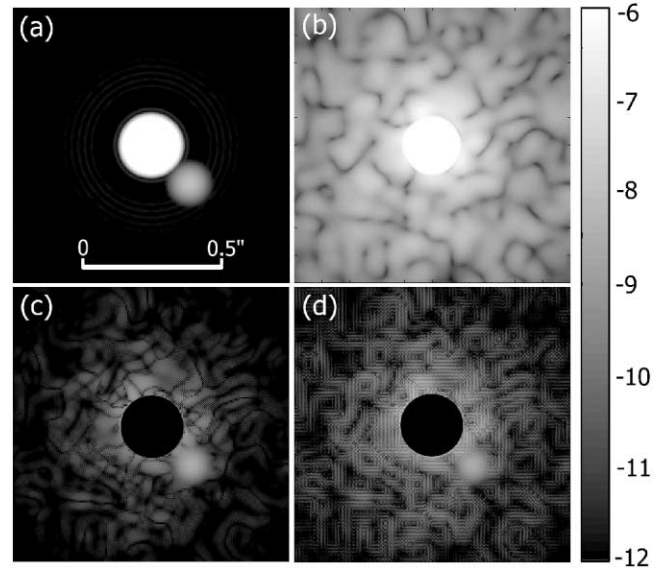


FIG. 3.—Halo suppression by destructive interference in the focal plane. (a) Intensity of a star halo ( $\log_{10}$  gray scale running from  $10^{-6}$  to  $10^{-12}$  peak) calculated for an ideal, deep, radial Chebyshev apodization (IEEE 1979) of an unobstructed circular aperture, adjusted for a halo at  $10^{-12}$  level, with a companion of  $10^{-8}$  star and  $0.2$  separation. This mask has transmission of  $7.5\%$  and doubles the diffraction-limited image width. The scale is shown for  $D = 4 \text{ m}$  ( $D_{\text{eff}} \sim 2 \text{ m}$ ) and  $\lambda = 500 \text{ nm}$ . (b) Halo modeled for predominantly low-order residual errors in the mask (power spectrum as  $\kappa^{-5.3}$  and strength described in text). (c) Halo now reduced by destructive interference with an antihalo, modeled for  $5\%$  bandwidth as described in the text. (d) Same as (c), but including the effect of a spatial light modulator with discrete pixels subtending  $\lambda/3D$ .

terference would then further reduce the halo. A planet image would be interpreted by the system as a speckle but could not be suppressed, since it is incoherent with the starlight. Techniques for complex amplitude control with deformable mirrors and spatial light modulators are described by Gonsalves (1997), Roggemann & Lee (1997), and Littman et al. (2003).

The additional reduction achievable in this way depends on bandwidth because of the radial stretching of speckles with wavelength. Remembering that phase changes by  $\pi$  for a radius change of  $\lambda/D_{\text{eff}}$  (Fig. 1b), we find  $I/I_0 \approx (\pi\phi/2)^2 (\Delta\lambda/\lambda_0)^2$ , where  $\Delta\lambda$  is the full bandwidth and  $\phi$  is the field radius in units of  $\lambda/D_{\text{eff}}$ .  $D_{\text{eff}}$  is the effective aperture for resolution after apodization.

The value of this second approach is that the accuracy now required for additional wave-front and amplitude control is greatly relaxed, because the complex amplitude to be adjusted is that of the weak interfering beam, not the full starlight beam. Thus, no matter how faint the starting halo, if we desire additional suppression by a factor of 100, the accuracy required in measuring and setting the antihalo is only  $\sim 0.1$  rad in phase and  $10\%$  in amplitude. Such modest requirements are readily achievable with liquid-crystal modulators of limited phase resolution.

Figure 3 shows an example of suppression at the level required for detection of close-by Earth-like planets. The case modeled is a  $4 \text{ m}$  space telescope, heavily apodized for less than  $10^{-12}$  suppression but degraded by residual amplitude and phase errors that result in a halo of  $2 \times 10^{-7}$  at  $0.2$ . When the focal plane nulling is applied, cancellation to a level of  $3 \times 10^{-10}$  is obtained, even allowing for  $5\%$  bandwidth. To minimize photon and speckle noise, measurements from six to 10 bands would be combined. Optimum settings for the global

and local correction elements would be worked out together. In this example, the required accuracy for the antihalo setting is greater than 100 times more relaxed than that assumed for the initial direct pupil correction (0.2 nm rms in wave front and 0.25% in intensity at 0.25 m scale).

## 5. DISCUSSION

In general, a servo correction system will be necessary to repeatedly correct small distortions that develop in the wave front. Only a few photons per speckle need be recorded over the full spectral band before a useful correction can be made. Repeated corrections made in this way will ensure that the halo flux is at the minimum possible level, and since each speckle is corrected before it has a chance to build up to more than a few photons, speckle noise in each cycle is held close to the level of halo photon noise.

This approach is valid for both ground and space telescopes. The main differences are in the achievable suppression limit and in the servo cycle time (Angel 2004). For ground telescopes, the wave front is continuously perturbed by evolving atmospheric turbulence. While some evolution can be predicted and compensated, there will remain an unpredictable compo-

nent that causes speckles at the few photon level to develop on a scale of a few tenths of a millisecond, depending on telescope aperture and seeing conditions. The corresponding halo brightness for telescopes of 8–30 m aperture at  $\sim 1 \mu\text{m}$  wavelength is likely to be  $\sim 10^{-6}$  to  $10^{-7}$  of the star. For optical coronagraphs in space, the relative stability of the wave front will permit much better halo suppression. But once the halo is at a level below that of the zodiacal background, there is little advantage in going further. For a telescope of a few meters aperture imaging at  $\sim 0.5 \mu\text{m}$ , this limit corresponds to  $\sim 10^{-9}$  of the star. In the photon noise limit, limiting sensitivity to exoplanets varies as (halo intensity)  $\times$  (cycle time) and is comparable for these ground and space telescope examples.

The level of suppression needed for ground telescopes should be achievable by method I with a single very fast-acting deformable mirror. The method has the advantage, mentioned above, that complex diffraction spikes from very large segmented mirrors can be suppressed with little loss of light. For the much higher suppression needed in space, the active halo nulling method will be preferred.

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