Astron. Astrophys. 338, 106–110 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Preliminary results of dark-speckle stellar coronography

A. Boccaletti[1], **A. Labeyrie**[2], **and R. Ragazzoni**[3]

[1] DESPA, Observatoire de Meudon, 5 place Jules Janssen, F-92195 Meudon, France (Boccalet@despa.obspm.fr)
[2] Collège de France & Observatoire de Haute Provence F-04870 Saint Michel l'Observatoire, France (Labeyrie@.obs-hp.fr)
[3] Astronomical Observatory of Padova, vicolo del'Observatorio 5, I-35122 Padova, Italy (Ragazzoni@astrpd.pd.astro.it)

Received 2 October 1997 / Accepted 22 June 1998

Abstract. The dark-speckle method (Labeyrie 1995) combines features of speckle interferometry and adaptive optics to provide images of faint circumstellar material. We present preliminary results of observations, and simulations concluding to the feasibility of exo-planet imaging from the ground. Laboratory simulations with an avalanche photodiode indicate the detectability of a stellar companion of relative intensity 10^{-6} at 5 Airy radii from the star. New, more general, expressions for the signal-to-noise ratio and integration time are given. Comparisons with direct long-exposure imaging indicate that the method improves the detectability of circumstellar nebulosity, faint companions and planets.

Key words: planetary systems – stars: low-mass, brown dwarfs – techniques: interferometric – binaries: close - stars: individual: HD 144217

1. Introduction

Extra-solar planets (Mayor &Queloz 1995, Marcy & Butler 1996) can, in principle, be seen in ground-based images using the light cancellation in dark speckles to remove the halo of star light (Labeyrie 1995). Long-exposures with high-performance adaptive optics and a correction of the seeing-induced shadow pattern on the telescope's pupil are also proposed by Angel (1994). A less extreme atmospheric correction is needed with the dark-speckle method. Both methods are expected to reach the 10^{-9} relative intensity needed to detect a Jupiter-like planet near its parent star. Related space-based techniques are also considered (Malbet et al. 1995, Gezari et al 1997). In the longer term, resolved images of detected exo-planets will in principle be obtainable even from the ground with long-baseline interferometric arrays (Labeyrie 1996).

The "dark-speckle" method exploits the light cancellation effect occuring in random coherent fields according to the Bose-Einstein statistics. Although adaptive optics can reconstruct the Airy peak, and possibly the first few rings, in the focal image of a bright star, the degree of "seeing" correction which it provides cannot be good enough to remove the fluctuating speckles in the surrounding zone of the Airy pattern. Coronagraphic devices (Lyot 1930, Bonneau et al. 1975, Mauron 1980, Malbet 1996, Gay & Rabbia 1996, Roddier & Roddier 1997) can remove the steady and organized part of the straylight, i.e. the first few Airy rings if they emerge from the boiling speckled halo, and even if they are burried but remain detectable with the dark speckle analysis.

One is therefore left with the problem of extracting as much information as possible from this speckled halo. Destructive interference in the star light occasionally causes a dark speckle to appear here and there. When this happens at the position of the planet's own faint Airy peak, the darkening cannot be as deep as elsewhere. The planet's Airy peak, also restored by the adaptive optics, indeed has a rather stable intensity, which adds to the star's local intensity. The intensity histogram is therefore locally distorted, and suitable algorithms can display the local distorsions in the form of a cleaned image. The exposures must be shorter than the turbulence life time. With a large telescope and hours of integration, a planet, typically 10^{9} times fainter than the parent star, is expected to become visible.

2. Signal to noise ratio

To calculate the method's sensitivity in a more general way than done by Labeyrie (1995), we first follow his derivation to the point where he calculates the signal-to-noise ratio.

The different photon distribution from the star and the planet defines the signal-to-noise ratio SNR, and according to the central limit theorem:

$$nP_*(0)[1-P_0(0)] = SNR\sqrt{nP_*(0)} \quad (1)$$

where $P_*(k_*)$ and $P_0(k_0)$ are the probabilities to detect k_* and k_0 photons originating respectively from the star and from the planet, per pixel in a short exposure, and where n is the total number of short exposures. Replacing the values of $P_*(0)$ and $P_0(0)$ in Eq. (1), we obtain:

$$SNR = (1-e^{-\overline{k_0}})\sqrt{\frac{n}{1+\overline{k_*}}} \quad (2)$$

The calculation of signal to noise ratio given in Labeyrie 1995 assumed $\overline{k_*} \gg 1$, which is unnecessarily restrictive, and unrealistic in some of the cases of interest. As suggested by one of us

Send offprint requests to: A. Boccaletti@despa.obspm.fr

(RR), a more general analysis can be made under the assumption that $\overline{k_0} \ll 1$ and $\overline{k_*} \gg \overline{k_0}$. Eq. (2) then becomes:

$$SNR \approx \overline{k_0}\sqrt{\frac{n}{1+\overline{k_*}}} \qquad (3)$$

if j is the number of pixels per speckles, thus:

$$(SNR)^2 \approx \frac{\frac{n}{j}(j\overline{k_0})^2}{j+j\overline{k_*}} = \frac{n'\overline{K_0}^2}{j+\overline{K_*}} \qquad (4)$$

Where $\overline{K_0}$ and $\overline{K_*}$ are the number of photons per speckle in a short exposure, respectively for the planet and the star.

The variables used in Labeyrie 1995 were:

$$n' = \frac{T}{t}, \quad \frac{\overline{K_*}}{\overline{K_0}} = \frac{R}{G} \quad \text{and} \quad G\overline{K_*} = tN_*$$

where T is the total integration time, t the short exposure time, R the star/planet brightness ratio, G the gain of the adaptive optics or the ratio between the Airy peak and the halo of speckles, N_* the total number of photons per second detected from the star.

It provides a new expression for the SNR:

$$SNR = \overline{K_0}\sqrt{\frac{n'}{j+\overline{K_*}}} = \frac{tN_*}{R}\sqrt{\frac{n'}{j+\frac{tN_*}{G}}} = \frac{N_*}{R}\sqrt{\frac{tT}{j+\frac{tN_*}{G}}} \qquad (5)$$

The sampling j should be fine enough to exploit the darkest parts of the dark speckles, for a given threshold of detection ϵ, linking the performance of the adaptive optics (G) and the brightness ratio (R). The intensity across a dark speckle may be coarsely modelled as a cosine function of the position ρ by:

$$I(\rho) = I_h\left(1-\cos\frac{2\pi\rho}{\sqrt{j}}\right) \qquad (6)$$

where I_h is the mean intensity and $\sqrt{j}$ the speckle size. The intersection between $I(\rho)$ and the line $y = \epsilon I_h$ gives s, the size of the pixel over which the light is integrated. It limits the minimal measurable intensity ϵI_h (with $0 < \epsilon \ll 1$). A detailed calculation gives $s \approx 1.27\sqrt{\epsilon}\frac{\lambda}{D}$.

We can assume that $\epsilon = G/R$. Indeed, if I_0 is the intensity of the Airy peak, $\epsilon = \frac{\epsilon I_h}{I_h} = \frac{\epsilon I_h}{I_0}\frac{I_0}{I_h} = \frac{G}{R}$

We also assume in the following that a planet can be seen if its own intensity is higher than ϵI_h.

Now we are able to calculate a value of j:

$$j = \frac{(\lambda/D)^2}{s^2} = \frac{(\lambda/D)^2}{1.27^2\epsilon\,(\lambda/D)^2} = 0.62\frac{R}{G} \qquad (7)$$

Recent numerical simulations (Boccaletti 1998) have shown that R/G should not exceed 10^3 to retain a reasonable value of the sampling parameter j.

The recorded level is I_h, but with dark speckles this residual level decreases to ϵI_h, where ϵ depends mainly on the adaptive optics performance.

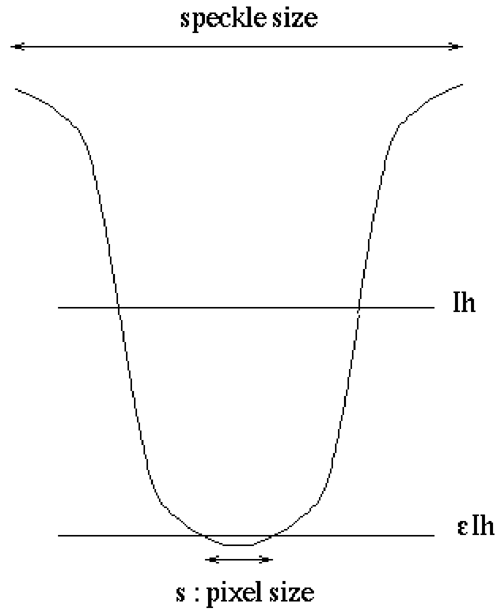

Fig. 1. Shape of a dark speckle according to Eq. (6). If I_h is the mean intensity, integration on a pixel of size s yields an intensity ϵI_h.

With the value of j obtained, the SNR expression becomes:

$$SNR = \frac{N_*}{R}\sqrt{\frac{tT}{0.62\frac{R}{G}+\frac{tN_*}{G}}} \qquad (8)$$

Solving for R, leads to a third-degree equation:

$$0.62R^3 + tN_*R^2 = \frac{GtTN_*^2}{(SNR)^2} \qquad (9)$$

The Cardan method gives a single positive solution from which we derive a final expression for the integration time.

$$T = \left(\frac{SNR}{N_*}\right)^2\frac{R}{Gt}(0.62R^2 + tN_*R) \qquad (10)$$

With the following values : $R = 10^9$; $D = 8m$; $G = 10^6$; $SNR = 5$; $m_v = 2.5$; $q = 0.2$; $\Delta\lambda = 100nm$ and $t = 20ms$, we find 2.7 hours of integration, i.e. 50% more than the result given by Labeyrie.

Angel's discussion (1994) of the long-exposure method leads him to the following expression:

$$R = \frac{G}{SNR}\sqrt{\frac{T}{\Delta t_{opt}}} \qquad (11)$$

where Δt_{opt} is the optimum short exposure time. Using again the same values, Eq. (11) gives a limiting brightness ratio of $1.4.10^8$ and the typical brightness ratio of 10^9 would be reached in 140 hours. The long-exposure approach would in principle be more sensitive if the adaptive optics and shadow pattern compensation could be made extremely good. It is however less sensitive with current levels of adaptive performance.

In fact, the difference between the dark-speckle and direct-long-exposure methods is more subtle, and both work in different regimes. A critical value of the photon stellar flux (N_{*c}) can

Table 1. Brightness ratio and SNR obtained with a photon-counting avalanche photodiode, for two values of the sampling parameter j. The number of zero-photon events was counted on 250000 short exposures of $100\mu s$, totalling $25s$ of integration. The SNR was calculated from Eq. (1).

j	R_{max}	R	0 ph. (star)	0 ph. (star +planet)	SNR
80	440000	15000	136796	110377	71.4
		150000	87672	85546	7.2
		360000	82340	80625	5.9
144	790000	560000	111044	107946	9.3
		950000	155959	150017	4.0

be easily calculated by equalizing Eq. (10) and Eq. (11) for the same value of the total integration time (T). It leads to a second degree equation in N_*, with a single positive root:

$$N_{*c} = \frac{G + \sqrt{G^2 + 4 \times 0.62GR}}{2t} \quad (12)$$

Therefore, if the photon flux is above N_{*c}, the dark-speckle method is more efficient than the long exposure and, below this limit the direct imaging is better. N_{*c} strongly depends on the adaptive optics. Let us take a numerical exemple. If the goal is to reach a 10^9 brightness ratio with a gain of 10^6 and $20ms$ exposures, the photon flux must be higher than $1.27.10^9 photons/s$, which can be achieved with a large aperture and wide bandwidth ($9.3.10^9$ph/s for $m_v = 0$, $D = 2.4m$, $\Delta\lambda = 100nm$ and 20% efficiency). However, for a space telescope with adaptive optics, the speckle lifetime is under control with values of the order of $1s$ for exemple. Thus, N_{*c} is decreased to $2.54.10^7 photons/s$, which is less restrictive. However, the telescope should not be so large as to provide a partially resolved image of the star, since it would fill-in the dark speckles.

3. Dark speckle lifetime

Because the number of photon-events detected per pixel in each exposure is critical, these exposures should be as long as possible without degrading too much the darkness of the dark speckles. The optimal value is obviously shorter than the usual speckle lifetime considered by Roddier, Gilli & Lund (1982). A tentative lower limit can be estimated by linearly scaling the speckle lifetime in proportion to the dark speckle size defined by Eq. (7). It leads to impossibly short exposures for large R values. However, since the adaptive optics decreases the wave disturbance, it increases markedly the speckle lifetime at positions close to the Airy peak, depending upon the factor $n\frac{\lambda}{D}$, where n is the number of actuators across the pupil containing n^2 of them (Ryan 1996). The optimal exposure time is therefore dependant upon the adaptive optics performance.

4. Simulation and results

To assess the dark-speckle method we did a laboratory simulation using a single-pixel photon-counting detector, in the form of an avalanche photodiode. The star and planet were simulated by two He-Ne lasers, with adjustable attenuators. A Lyot-type coronagraph permitted to remove the star's Airy peak and rings, thus decreasing the local halo intensity 10 to 15 times. Artificial "seeing" was generated with a moving scatterer, selected to provide a Strehl ratio approaching that typical of current adaptive optical systems. The equivalent peak/halo gain was $G = 3.4.10^3$. The flux of the central star was 44.10^6 photons/s. Calculating an histogram of the detected photon events, we determined the SNR by comparing the number of zero-photon events with the planet turned on and off. As listed in Table 1, the results strongly depend on the sampling parameter j. They are consistent with Eq. (7) which gives the maximum brightness ratio (R_{max}) theoretically reachable. In these laboratory tests, the dark-speckle analysis outperforms the long exposure when the sampling exceeds $144\, pixels/speckle\, area$. In this experiment the short exposure time ($100\mu s$) is about 100 times shorter than the speckle lifetime ($10ms$). Available photon counting camera do not yet allow quite as short exposure.

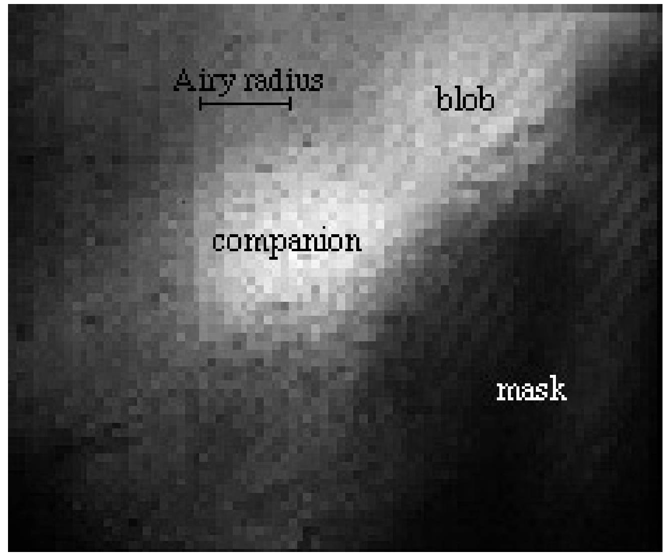

Fig. 2. Laboratory simulation of stellar companion detection with the dark speckle method. The artificial companion, 966 times fainter than the star, is at the center of the dark map, emerging from the halo. A coronagraphic mask, which hides the star's central peak is visible in the lower right corner. The blob seen in the upper right part of the field is a "static speckle" caused by permanent aberrations and removable with a reference star.

We also used the CP40 photon-counting camera developed by Foy and Blazit (Blazit 1986). It has pixels of $50\mu m$ and a rather low saturation level of $50000 photons/s$. Each pixel has a lower dark noise than an avalanche photodiode, but a much slower response. We used the algorithm described in Labeyrie (1995), generating a "dark map" by counting, in each pixel, the number of $20ms$ exposures which contribute zero photon. As contributions from successive $20ms$ exposures are accumulated in the dark map, a planet's Airy peak is expected to emerge as a black dot among background noise. To obtain the cleaned

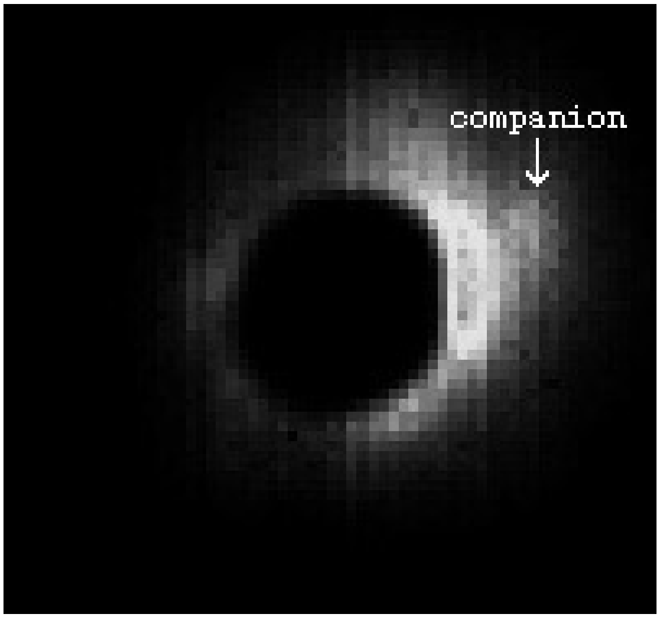

Fig. 3. Cleaned image, generated through dark-speckle analysis, of the multiple star HD144217(β Sco). A companion (β Sco B) appears near the masked star image. (mask diameter= $0.5''$, $F/D = 1200$)

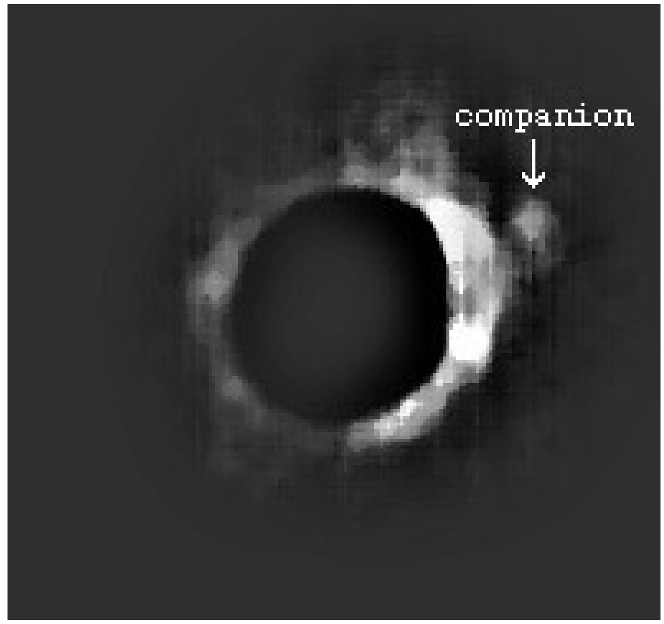

Fig. 4. Same image enhanced with unsharp mask and high pass filter to emphasize the contrast and median filter to smooth the image at the speckle scale.

image, results are displayed in positive form using, for example, an inverse square law.

The CP40 discriminates between events featuring zero photoelectron and those featuring one or more photoelectron/pixel/exposure. Adding all exposures generates an image which brings out faint companions better than would a similarly long exposure on a CC D detector.

The flux of the central star was $5.3.10^6$ photons/s, and the gain of the adaptive optics was about 1556. The optical system operated at $\lambda = 0.67\mu m$, $F/D = 3200$, and the mask diameter was 0.34", i.e. it covered the central 2 rings of the Airy pattern. The planet was located near the fifth ring of the diffraction pattern.

Fig. 2 shows that a companion 966 times fainter is well detected in 116 seconds. The SNR measured on a speckle size region (37×37 pixels) is 799, while the dark-speckle model predict an SNR of 1008. This model does not take into account the halo shape which can explain the 20% discrepancy. These initial results, where the companion is brighter than the halo, are very modest with respect to the performance expected at a later stage, but have provided useful insight for improving the instrument.

Currently, as seen in Figs. 2 and 3, the detection sensitivity is limited by the presence of spurious blobs in the cleaned image. These are caused by static aberrations and coronagraphic mask effects. These residual blobs may be substracted from data obtained on a reference star.

Finally, dark-speckle data have been recorded at the 152cm telescope of Haute-Provence, using, during a single night, the BOA adaptive optics system (Madec 1997) developped by the Office National d'Etudes et de Recherches Aérospatiales (ONERA). This system, optimized for visible light, reaches a Strehl ratio of about 0.4 at $0.6\mu m$ in long exposures and higher in short exposures. 30 minutes of observation, with an interference filter centered at $0.67\mu m$ ($\Delta\lambda = 100$Å), evidenced the faint component of the spectroscopic binary HD144217 ($\alpha = 16h05'26$", $\delta = -19°48'18$", $V = 2.62$). On the detector, the flux from the primary was only 11860 photons/s. The angular separation is about 0.45" with an uncertainty due to the mask offset. Owing to the low elevation of the star, the adaptive optics gain was only 12. The SNR measured on 16×16 pixels is 168 and allows to derive from Eq. (10) a brightness ratio of 88, corresponding to a 4.8 magnitude difference. On the long exposure synthesized from the same data (1 photon-events analysis) the SNR is very similar, but a direct imaging should give a SNR of 42 according to Eq. (11). However, a recent measurement of lunar-occultation (Evans 1983) gives $\Delta m = 3.3$. In this case, dark-speckle analysis should provide a very good detection with a SNR of 756 instead of 168. Unfortunately, the Hipparcos mission failed to detect the companion, probably because the Hipparcos satellite is unable to achieve $\Delta m > 4$ with small angular separation, which is consistent with our data. More observations are needed to verify the companion magnitude.

A continuing observing program is initiated.

5. Conclusion

The simulations and tentative observations lead to the following remarks:

1. One would like to sample as densely as possible to reach the bottom of the dark speckles, but there should be enough photons per pixel. The optimal sampling is therefore critical

and we guess that it should be about 500 pixels per speckle area.

2. A fast photon-counting camera with a low dark noise, high saturation level and many pixels is needed.

3. The observations required a narrow-band filter since the diffraction and speckle pattern are color-dependant. The speckles are themselves dispersed radially. To increase the bandwidth usable in speckle interferometry, Wynne designed a chromatic lens with magnification inversely proportional to wavelength (Wynne 1979). D. Kohler built a Wynne corrector and we found it efficiently applicable to the present situation, where the speckle's wavelength dependance is more nearly a linear scaling. The resulting smearing of the planet's peak is acceptable if the spectral band remains less than 100 nm.

4. Different types of apodisation can be achieved, using a classical Lyot coronagraph, the interference coronagraph of Gay & Rabbia (1996), or the phase-mask coronagraph of Roddier & Roddier (1997). Both recent systems favor the detection of planets closer to the central star's Airy peak. Laboratory simulations with these varied devices are considered to compare their respective efficiencies.

Our simulations verify the theoretical expressions given for the signal to noise ratio. The SNR measured from the photon-number variance (Eq. (1)), is consistent with the SNR expected from the model (Eq. (10)). In these preliminary tests, we had to use an interference filter and low saturation level camera which provides a weak signal. We were consequently unable to reach enough sensitivity for detecting extrasolar-planets or even brown-dwarf companions.

The dark-speckle method is also applicable to space telescopes. Even without turbulence, optical defects create static speckles which can be made to fluctuate with a few actuators, arranged in the form of an active optics system, or a fast random scatterer. We proposed a "dark-speckle camera", the Faint Source Coronagraphic Camera for the Hubble Space Telescope (Gezari et al 1997). The project is reconsidered for the New Generation Space Telescope.

IR wavelengths are of interest for the detection of extrasolar planets, for two reasons: the planet's contrast is improved and, turbulence is easier to correct at these wavelengths. The forthcoming developement of bidimensional sensors with low read noise should allow red and IR work.

Acknowledgements. We wish to thank D. Kohler and G. Knispel who made simulations possible, as well as D. Mourard and A. Blazit for the CP40 camera assistance. We are also grateful to the ONERA team for providing the adaptive optics system.

References

Angel J.R.P., 1994, Nat 368, 203
Blazit A., 1986, "A 40mm photon counting camera", procs. Coll. SPIE 702
Boccaletti A., 1998 "Simulations of Dark-Speckle for the Hubble Space Telescope", ASP Conference Series, vol. 134, p. 292
Bonneau D., Josse M., Labeyrie A., 1975, "Imaging techniques in Astronomy", proc. Utrecht Symp. de Jager/Nieuwenhuijzen eds. Reidel, 403
Evans D.S., 1983, Catalogue of occultation double-star observations
Gay J., Rabbia Y., 1996, "Principe d'un coronographe interférentiel", CR. Acad. Sci. Paris, t. 332, Serie II b, p. 265-271
Gezari D. Y., Crotts A., Danchi W., et al., 1997, "Faint Source Coronagraphic Camera for the Hubble Space Telescope", Columbia University and Ball Aerospace Systems Division, proposal in response to NASA AO-96-OSS-3
Labeyrie A., 1995, A&A 298, 544-548
Labeyrie A., 1996, A&AS 118, 517
Lyot B., 1930 Comptes rendus, 191, 834
Madec P.Y., 1997, Journée technique de l'Observatoire de Paris, 2^{eme} Journée R&D associée à l'optique adaptative et aux calculateurs temps réels, p 159.
Malbet F., Yu J.W, Shao M., 1995, PASP 107, 386-398
Malbet F., 1996, A&AS 115, 161-174
Marcy G. W., Butler R. P. 1996, ApJ 464, L147-L151
Mauron, 1980, PhD thesis, University of Marseille
Mayor M., Queloz D., 1995, Nat 378, 355
Roddier F., Roddier C., 1997, PASP 109, 815
Roddier F., Gilli J.M., Lund G., 1982, J. Optics 13, 263
Ryan P., 1996, PhD Thesis, University of Arizona
Wynne C.G., 1979, Opt. Comm., 28, 21