Self-Coherent Camera At The Palomar Observatory

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ABSTRACT

The future Extremely Large Telescopes will provide a high angular resolution enabling the study of small circumstellar disk structures, Jupiter-like planets, and maybe super-Earths. The foreseen instrumentation will be composed of classical adaptive optics followed by a coronagraph and, an active and passive speckle minimization. The active minimization requires a focal plane wavefront sensor that measures the electric field from the coronagraphic science image to cancel the non-common path errors. Our team uses the self-coherent camera (SCC). After demonstrating high performance in laboratory (1e-8 raw contrast between 4 and 13 lambda/D), we implemented the SCC at the Palomar telescope on the stellar double corongraph (SDC). We present below the first results obtained at the telescope.

Keywords: High contrast imaging, Exoplanets, Adaptive optics, Coronagraph, high angular resolution, wavefront sensor

1. INTRODUCTION

From indirect detections of 3500 exoplanets [*], astronomers derived statistics on orbital parameters of the planets, sometimes their radius,[1,2] and they put constraints on the frequency of close-in planets.[3,4] Then, transits enabled first measurements of spectra of the upper layers of exoplanet atmospheres.[5] Today, to constrain the models of planet formation, one priority is the determination of the frequency of planets with long-periods. Another priority is the study of the exoplanet atmospheres. Direct imaging is the technique that enables both studies.

The challenge comes from the small angular separation and the high contrast between the star and its planet. Specific instruments are thus required involving classical adaptive optics, coronagraph to reduce the starlight, and active/passive speckle minimization. Sphere/VLT[6] and GPI/Gemini[7] were installed on the 8m-class telescopes to probe young nearby exoplanet systems. The preliminary results show a low frequency of massive exoplanets,[8–21] but numerous circumstellar disks with structures that can be created by super-Earths or Jupiter-like exoplanets.

The future Extremely Large Telescopes will provide a higher angular resolution to study small disk structures, and they will enable to probe Jupiter-like planets, and maybe super-Earths. The foreseen instrumentation will be composed of classical adaptive optics followed by a coronagraph and an active and passive speckle minimization. The active minimization requires a focal plane wavefront sensor (FPWFS) that measures the electric field from the science image. Our team proposed such a FPWFS called self-coherent camera (SCC).[22–28] After demonstrating high performance in laboratory (1e-8 raw contrast between 4 and 13 lambda/D),[29–33] we implemented the SCC at the Palomar telescope. We quickly recall the principle of the SCC (§ 2). Then, we present the first results in § 3 and § 4.

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2. PRINCIPLE OF THE SELF-COHERENCE CAMERA

The self-coherent camera (SCC) has already been presented in several papers.[22–33] We briefly recall the principle of the technique and how we use the spatial modulation of the speckles to control a deformable mirror and create a dark hole in the science image. We encourage the reader to refer to the previous papers for exhaustive parametric studies of the instrument configuration.

Fig. 1 presents a scheme of the association of a self-coherent camera with a focal plane phase mask coronagraph. The beam incoming from the telescope hits a deformable mirror and converges on the focal plane mask of

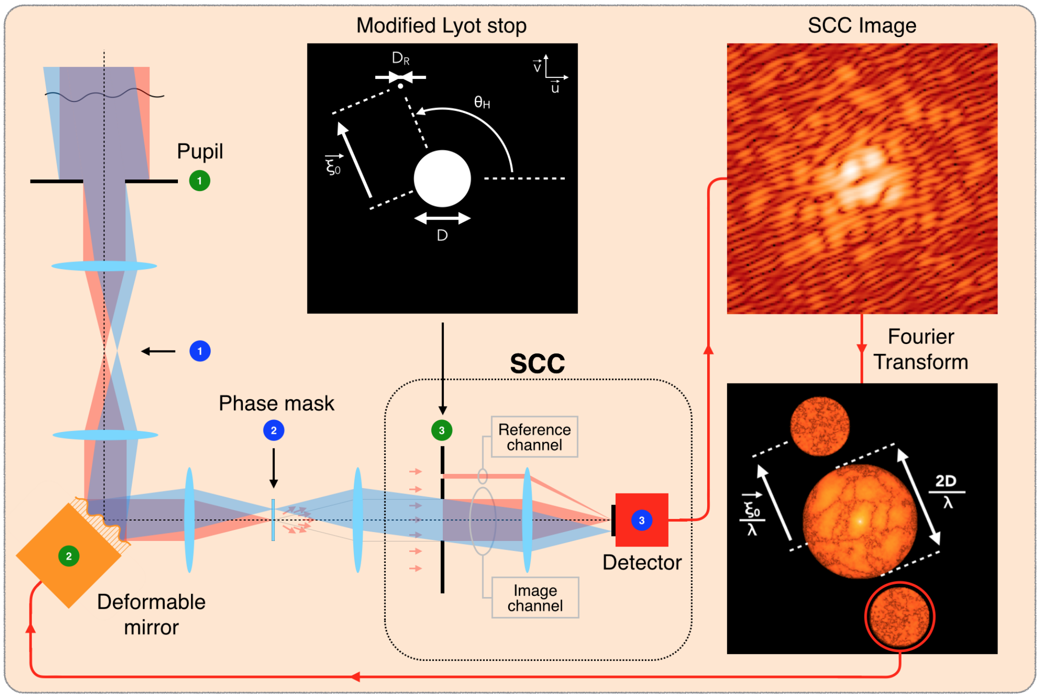

Figure 1. *Association of a self-coherent camera, a coronagraph and a deformable mirror. Top center: SCC modified Lyot stop. Top right: SCC coronagraphic image with SCC spatially modulated speckles. Bottom right: Fourier transform of the SCC image.*

the coronagraph. The mask scatters the light of the on-axis source (e.g. the star, red beam in the figure) outside the geometrical pupil in the following pupil plane. There, a small reference hole is added to the classical Lyot stop to add a reference channel to the science channel. We recall that the light of any off-axis source (planet for example) as well as the light that induces the stellar speckles in the science image because of aberrations are not affected by the focal plane mask and thus, go through the science channel. The reference channel contains only part of the stellar light that is scattered by the focal plane mask. The last optics make the two channels interfer in a Fizeau pattern in the SCC image (top right). In this image, the stellar speckles are spatially modulated by fringes whereas the planet image is not modulated as its light is not coherent with the stellar light that goes through the reference channel. The central peak of the Fourier transform of the SCC image (bottom right) is the sum of the autocorrelations of the speckle intensity, of the reference intensity, and of the planet intensity. The lateral peaks are the correlation between the reference complex field and the speckle complex field. To control the deformable mirror, we select only one of the lateral peaks that directly leads to an estimation of the complex electric field associated to the stellar speckles.[31–33]

3. SCC ON THE STELLAR DOUBLE CORONAGRAPH

The stellar double coronagraph instrument[34] has two focal planes for phase masks (vortex1 and vortex2) and two Lyot stops (1 and 2, Fig. 2). We did not use the vortex1 plane. We put a mask in the Lyot stop 1 to select

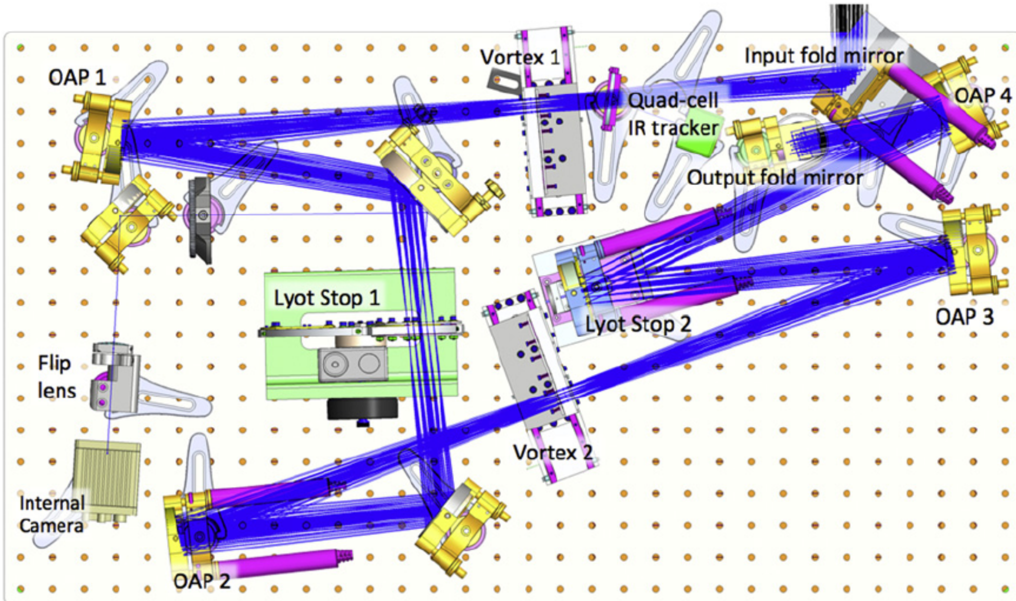

Figure 2. *Scheme of the stellar double coronagraph instrument (SDC) that is installed at the Palomar telescope.*

a 1.5m full pupil from the Palomar 4.5m obscurated pupil and we used a vortex coronagraph in the vortex2 plane. Then, we modified the Lyot stop 2 (Fig. 3) to implement a self-coherent camera (SCC). To choose the

Figure 3. *SCC modified Lyot stop. The classical stop is the large hole. The SCC reference hole is the small hole.*

diameter and the position of the reference hole, we measured the energy distribution in the Lyot stop plane after the SDC vortex using the internal source at K-band (Fig. 4). The radial profile of this image is given in Fig. 5. The energy at less than 0.5 pupil diameter (D) is due to aberrations. It is linked to the speckle energy. Outside the geometrical pupil ($r > 0.5D$), the energy decreases as expected from the theoretical model as r^{-4}. Given the

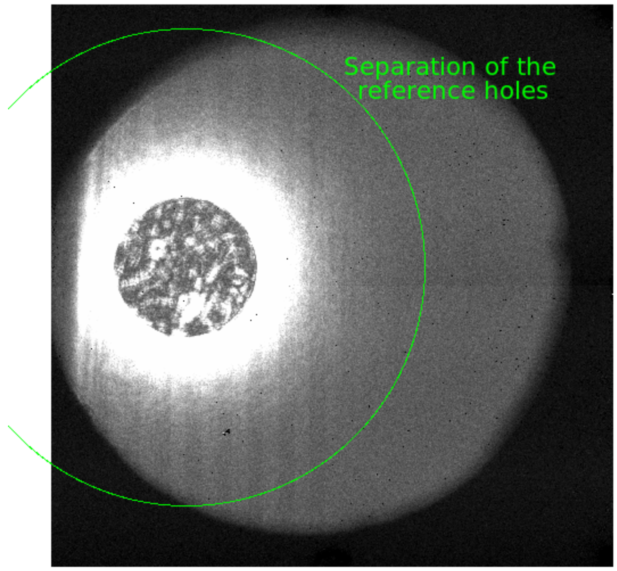

Figure 4. *Image giving the energy distribution in the Lyot stop plane after the Palomar vortex coronagraph.*

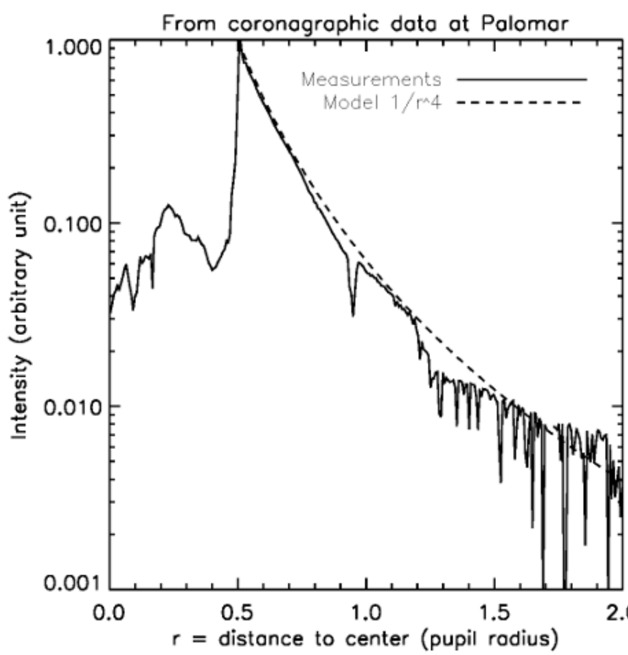

Figure 5. *Energy distribution in the Lyot stop plane after the Palomar vortex coronagraph (full line). The theory (dashed line) predicts a* $1/r^4$ *function outside the geometrical pupil.*

speckle energy, we choose the diameter and the reference hole so that the spatial fringes in the SCC image are detected with a good SNR. The diameter of the reference hole was 11 times smaller than the Lyot stop diameter (D). The center-to-center distance between the reference hole and the Lyot stop was $1.69\,D$.

4. RESULTS

We used the internal source and obtained SCC images (top in Fig. 6). The Fourier transform confirm the speckles are spatially modulated as there is energy in the lateral peaks (bottom in Fig. 6). The peaks in the

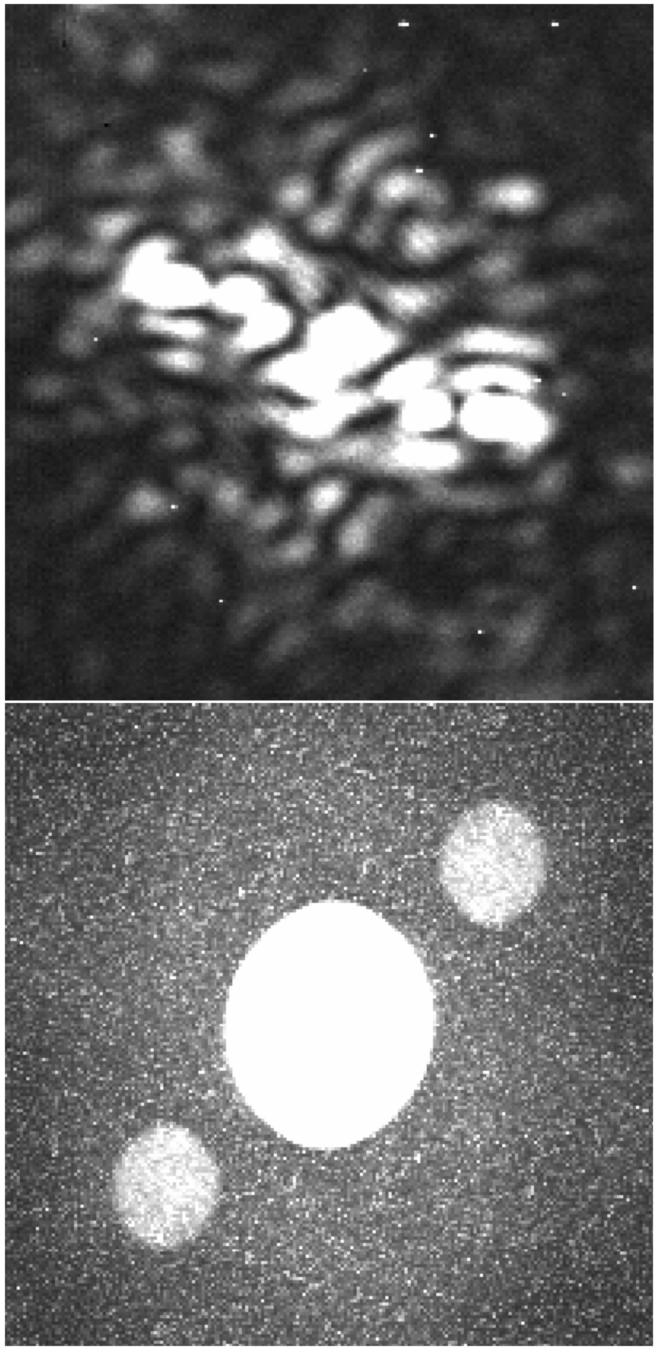

Figure 6. *Top: SCC image with spatially modulated stellar speckles. Bottom: Fourier transform of the SCC iamge.*

Fourier transform are not round because we had to use a cat-eye Lyot stop to correctly filter the stellar light (the magnification on the SDC bench was different from the one we assumed when designing the Lyot stop mask).

We used the SCC image to control the deformable mirror[31–33] and we minimized the energy of the speckles inside a disk of 5 FWHM radius. The images before (top) and after 4 iterations of correction (bottom) are showed in Fig. 7. The controled area is cleaned from speckles and the contrast is improved by a factor of 10 in 4 iterations

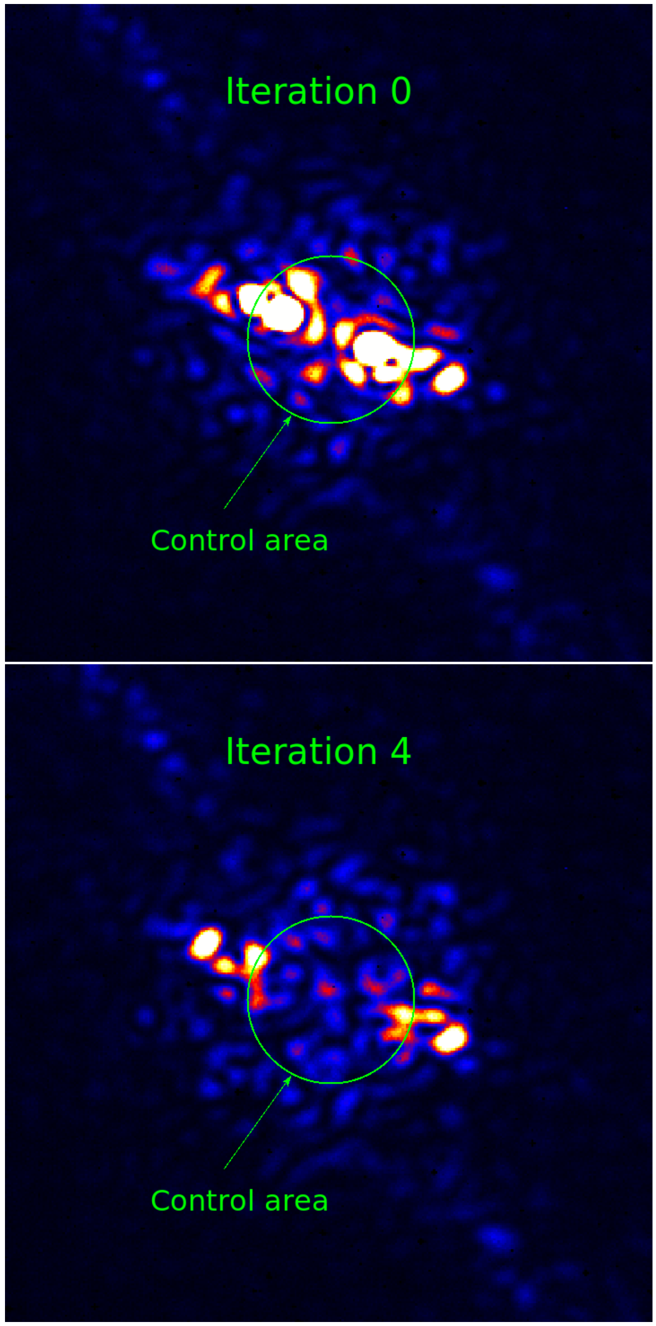

Figure 7. *Top: SCC image before controlling the deformable mirror. Bottom: SCC image after 4 iterations of correction using the SCC to control the deformable mirror.*

as showed in Fig. 8 that gives the normalized integrated energy inside the disk of 5 FWHM radius (1 is the initial energy). The initial speckle energy could not be attenuated by more than 10. Several reasons are to be studied: stability of the fringes in time, low flux level, stability of the image center on the detector. We plan new tests to understand the current limitations and to demonstrate the technique on-sky.

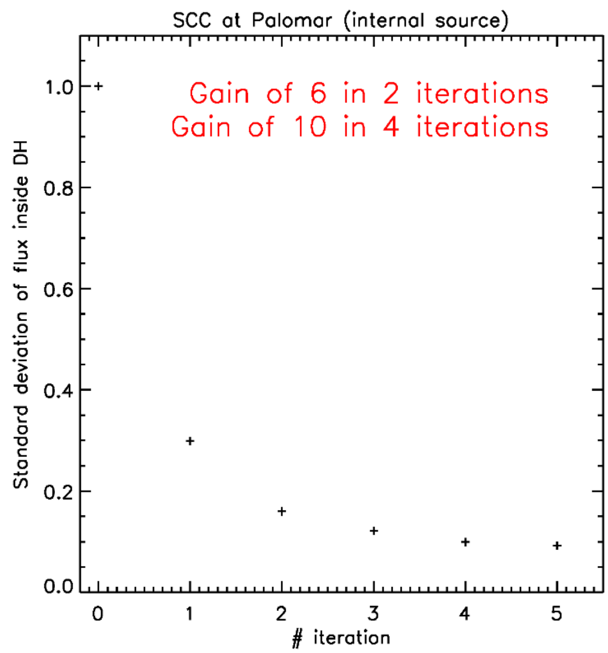

Figure 8. *Energy inside the disk of* 5 FWHM *radius for each iteration of correction controlled by the SCC. The initial energy is set to* 1.

5. CONCLUSIONS

The Self-Coherent Camera (SCC, a focal plane wavefront sensor) performance was demonstrated at the Paris Observatory in laboratory reaching very high contrast routinely. However, it had not been tested elsewhere than at the Paris Observatory before we started a collaboration with the stellar double coronagraph (SDC) team of the Palomar telescope. The SCC was easily and successfully implemented on the SDC bench adding a small hole in the classical coronagraphic Lyot stop. We demonstrated the performance of the technique using an internal source (because of bad weather) and a full-pupil of 1.5m (no spider, no obscuration): the self-coherent camera science images were used to control the Palomar deformable mirror in close-loop and enabled the reduction by a factor of 10 of the speckle energy behind a vortex phase mask coronagraph working in the near infrared.

Given the very good results, new tests are scheduled at the Palomar telescope. We will use the 4.5m obscurated pupil and do on-sky observations taking advantage of the SCC that can attenuate the speckle energy at any distance from the star (the closer to the star, the better the attenuation).

REFERENCES

[1] Udry, S. and Santos, N. C., "Statistical properties of exoplanets," *Annual Review of Astronomy & Astrophysics* **45**, 397–439 (Sept. 2007).

[2] Santos, N. C., "Extra-solar planets: Detection methods and results," *New Astronomy Review* **52**, 154–166 (June 2008).

[3] Butler, R. P., Wright, J. T., Marcy, G. W., Fischer, D. A., Vogt, S. S., Tinney, C. G., Jones, H. R. A., Carter, B. D., Johnson, J. A., McCarthy, C., and Penny, A. J., "Catalog of nearby exoplanets," *The Astrophysical Journal* **646**, 505–522 (July 2006).

[4] Cumming, A., Butler, R. P., Marcy, G. W., Vogt, S. S., Wright, J. T., and Fischer, D. A., "The keck planet search: Detectability and the minimum mass and orbital period distribution of extrasolar planets," *Publications of the Astronomical Society of the Pacific* **120**, 531–554 (May 2008).

[5] Seager, S. and Deming, D., "Exoplanet Atmospheres," *Annual Review of Astronomy and Astrophysics* **48**, 631–672 (Sept. 2010).

[6] Beuzit, J.-L., Feldt, M., Dohlen, K., Mouillet, D., Puget, P., Wildi, F., Abe, L., Antichi, J., Baruffolo, A., Baudoz, P., Boccaletti, A., Carbillet, M., Charton, J., Claudi, R., Downing, M., Fabron, C., Feautrier, P., Fedrigo, E., Fusco, T., Gach, J.-L., Gratton, R., Henning, T., Hubin, N., Joos, F., Kasper, M., Langlois, M., Lenzen, R., Moutou, C., Pavlov, A., Petit, C., Pragt, J., Rabou, P., Rigal, F., Roelfsema, R., Rousset, G., Saisse, M., Schmid, H.-M., Stadler, E., Thalmann, C., Turatto, M., Udry, S., Vakili, F., and Waters, R., "SPHERE: a planet finder instrument for the VLT," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7014** (Aug. 2008).

[7] Macintosh, B., Graham, J. R., Ingraham, P., Konopacky, Q., Marois, C., Perrin, M., Poyneer, L., Bauman, B., Barman, T., Burrows, A. S., Cardwell, A., Chilcote, J., De Rosa, R. J., Dillon, D., Doyon, R., Dunn, J., Erikson, D., Fitzgerald, M. P., Gavel, D., Goodsell, S., Hartung, M., Hibon, P., Kalas, P., Larkin, J., Maire, J., Marchis, F., Marley, M. S., McBride, J., Millar-Blanchaer, M., Morzinski, K., Norton, A., Oppenheimer, B. R., Palmer, D., Patience, J., Pueyo, L., Rantakyro, F., Sadakuni, N., Saddlemyer, L., Savransky, D., Serio, A., Soummer, R., Sivaramakrishnan, A., Song, I., Thomas, S., Wallace, J. K., Wiktorowicz, S., and Wolff, S., "First light of the Gemini Planet Imager," *Proceedings of the National Academy of Science* **111**, 12661–12666 (Sept. 2014).

[8] Biller, B. A., Close, L. M., Masciadri, E., Nielsen, E., Lenzen, R., Brandner, W., McCarthy, D., Hartung, M., Kellner, S., Mamajek, E., Henning, T., Miller, D., Kenworthy, M., and Kulesa, C., "An Imaging Survey for Extrasolar Planets around 45 Close, Young Stars with the Simultaneous Differential Imager at the Very Large Telescope and MMT," *The Astrophysical Journal Supplement Series* **173**, 143–165 (Nov. 2007).

[9] Kasper, M., Apai, D., Janson, M., and Brandner, W., "A novel L-band imaging search for giant planets in the Tucana and β Pictoris moving groups," *Astronomy and Astrophysics* **472**, 321–327 (Sept. 2007).

[10] Lafrenière, D., Doyon, R., Marois, C., Nadeau, D., Oppenheimer, B. R., Roche, P. F., Rigaut, F., Graham, J. R., Jayawardhana, R., Johnstone, D., Kalas, P. G., Macintosh, B., and Racine, R., "The Gemini Deep Planet Survey," *The Astrophysical Journal* **670**, 1367–1390 (Dec. 2007).

[11] Nielsen, E. L., Close, L. M., Biller, B. A., Masciadri, E., and Lenzen, R., "Constraints on Extrasolar Planet Populations from VLT NACO/SDI and MMT SDI and Direct Adaptive Optics Imaging Surveys: Giant Planets are Rare at Large Separations," *The Astrophysical Journal* **674**, 466–481 (Feb. 2008).

[12] Metchev, S. A. and Hillenbrand, L. A., "The Palomar/Keck Adaptive Optics Survey of Young Solar Analogs: Evidence for a Universal Companion Mass Function," *The Astrophysical Journal Supplement* **181**, 62–109 (Mar. 2009).

[13] Chauvin, G., Lagrange, A.-M., Bonavita, M., Zuckerman, B., Dumas, C., Bessell, M. S., Beuzit, J.-L., Bonnefoy, M., Desidera, S., Farihi, J., Lowrance, P., Mouillet, D., and Song, I., "Deep imaging survey of young, nearby austral stars . VLT/NACO near-infrared Lyot-coronographic observations," *Astronomy and Astrophysics* **509**, A52 (Jan. 2010).

[14] Heinze, A. N., Hinz, P. M., Sivanandam, S., Kenworthy, M., Meyer, M., and Miller, D., "Constraints on Long-period Planets from an L'- and M-band Survey of Nearby Sun-like Stars: Observations," *The Astrophysical Journal* **714**, 1551–1569 (May 2010).

[15] Rameau, J., Chauvin, G., Lagrange, A.-M., Klahr, H., Bonnefoy, M., Mordasini, C., Bonavita, M., Desidera, S., Dumas, C., and Girard, J. H., "A survey of young, nearby, and dusty stars conducted to understand the formation of wide-orbit giant planets. VLT/NaCo adaptive optics thermal and angular differential imaging," *Astronomy and Astrophysics* **553**, A60 (May 2013).

[16] Yamamoto, K., Matsuo, T., Shibai, H., Itoh, Y., Konishi, M., Sudo, J., Tanii, R., Fukagawa, M., Sumi, T., Kudo, T., Hashimoto, J., Kusakabe, N., Abe, L., Brandner, W., Brandt, T. D., Carson, J., Currie, T., Egner, S. E., Feldt, M., Goto, M., Grady, C., Guyon, O., Hayano, Y., Hayashi, M., Hayashi, S., Henning, T., Hodapp, K., Ishii, M., Iye, M., Janson, M., Kandori, R., Knapp, G. R., Kuzuhara, M., Kwon, J., McElwain, M., Miyama, S., Morino, J.-I., Moro-Martin, A., Nishikawa, J., Nishimura, T., Pyo, T.-S., Serabyn, E., Suto, H., Suzuki, R., Takami, M., Takato, N., Terada, H., Thalmann, C., Tomono, D., Turner, E. L., Wisniewski, J., Watanabe, M., Yamada, T., Takami, H., and Usuda, T., "Direct Imaging Search for Extrasolar Planets in the Pleiades," *Publications of the Astronomical Society of Japan* **65**, 90 (Aug. 2013).

[17] Biller, B. A., Liu, M. C., Wahhaj, Z., Nielsen, E. L., Hayward, T. L., Males, J. R., Skemer, A., Close, L. M., Chun, M., Ftaclas, C., Clarke, F., Thatte, N., Shkolnik, E. L., Reid, I. N., Hartung, M., Boss, A., Lin, D., Alencar, S. H. P., de Gouveia Dal Pino, E., Gregorio-Hetem, J., and Toomey, D., "The Gemini/NICI Planet-Finding Campaign: The Frequency of Planets around Young Moving Group Stars," *The Astrophysical Journal* **777**, 160 (Nov. 2013).

[18] Nielsen, E. L., Liu, M. C., Wahhaj, Z., Biller, B. A., Hayward, T. L., Close, L. M., Males, J. R., Skemer, A. J., Chun, M., Ftaclas, C., Alencar, S. H. P., Artymowicz, P., Boss, A., Clarke, F., de Gouveia Dal Pino, E., Gregorio-Hetem, J., Hartung, M., Ida, S., Kuchner, M., Lin, D. N. C., Reid, I. N., Shkolnik, E. L., Tecza, M., Thatte, N., and Toomey, D. W., "The Gemini NICI Planet-Finding Campaign: The Frequency of Giant Planets around Young B and A Stars," *The Astrophysical Journal* **776**, 4 (Oct. 2013).

[19] Wahhaj, Z., Liu, M. C., Nielsen, E. L., Biller, B. A., Hayward, T. L., Close, L. M., Males, J. R., Skemer, A., Ftaclas, C., Chun, M., Thatte, N., Tecza, M., Shkolnik, E. L., Kuchner, M., Reid, I. N., de Gouveia Dal Pino, E. M., Alencar, S. H. P., Gregorio-Hetem, J., Boss, A., Lin, D. N. C., and Toomey, D. W., "The Gemini Planet-finding Campaign: The Frequency Of Giant Planets around Debris Disk Stars," *The Astrophysical Journal* **773**, 179 (Aug. 2013).

[20] Brandt, T. D., McElwain, M. W., Turner, E. L., Mede, K., Spiegel, D. S., Kuzuhara, M., Schlieder, J. E., Wisniewski, J. P., Abe, L., Biller, B., Brandner, W., Carson, J., Currie, T., Egner, S., Feldt, M., Golota, T., Goto, M., Grady, C. A., Guyon, O., Hashimoto, J., Hayano, Y., Hayashi, M., Hayashi, S., Henning, T., Hodapp, K. W., Inutsuka, S., Ishii, M., Iye, M., Janson, M., Kandori, R., Knapp, G. R., Kudo, T., Kusakabe, N., Kwon, J., Matsuo, T., Miyama, S., Morino, J.-I., Moro-Martín, A., Nishimura, T., Pyo, T.-S., Serabyn, E., Suto, H., Suzuki, R., Takami, M., Takato, N., Terada, H., Thalmann, C., Tomono, D., Watanabe, M., Yamada, T., Takami, H., Usuda, T., and Tamura, M., "A Statistical Analysis of SEEDS and Other High-contrast Exoplanet Surveys: Massive Planets or Low-mass Brown Dwarfs?," *The Astrophysical Journal* **794**, 159 (Oct. 2014).

[21] Galicher, R., Marois, C., Macintosh, B., Zuckerman, B., Barman, T., Konopacky, Q., Song, I., Patience, J., Lafrenière, D., Doyon, R., and Nielsen, E. L., "The International Deep Planet Survey. II. The frequency of directly imaged giant exoplanets with stellar mass," *Astronomy and Astrophysics* **594**, A63 (Oct. 2016).

[22] Baudoz, P., Boccaletti, A., Baudrand, J., and Rouan, D., "The self-coherent camera: a new tool for planet detection," in [*IAU Colloq. 200: Direct Imaging of Exoplanets: Science Techniques*], Aime, C. and Vakili, F., eds., 553–558 (2006).

[23] Baudoz, P., Mas, M., Galicher, R., and Rousset, G., "The Self-Coherent Camera : a focal plane sensor for EPICS ?," in [*Adaptative Optics for Extremely Large Telescopes*], (2010).

[24] Baudoz, P., Mas, M., Galicher, R., and Rousset, G., "Focal plane wavefront sensor sensitivity for ELT planet finder," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7736** (July 2010).

[25] Baudoz, P., Mazoyer, J., Mas, M., Galicher, R., and Rousset, G., "Dark hole and planet detection: laboratory results using the self-coherent camera," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446** (Sept. 2012).

[26] Galicher, R. and Baudoz, P., "Expected performance of a self-coherent camera," *Comptes Rendus Physique* **8**, 333–339 (Apr. 2007).

[27] Galicher, R., Baudoz, P., and Rousset, G., "Wavefront error correction and earth-like planet detection by a self-coherent camera in space," *Astronomy and Astrophysics* **488**, L9–L12 (Sept. 2008).

[28] Galicher, R., Baudoz, P., Rousset, G., Totems, J., and Mas, M., "Self-coherent camera as a focal plane wavefront sensor: simulations," *Astronomy and Astrophysics* **509**, A31+ (Jan. 2010).

[29] Mas, M., Baudoz, P., Rousset, G., Galicher, R., and Baudrand, J., "Self-coherent camera: first results of a high-contrast imaging bench in visible light," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7735** (July 2010).

[30] Mas, M., Baudoz, P., Mazoyer, J., Galicher, R., and Rousset, G., "Experimental results on wavefront correction using the self-coherent camera," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446** (Sept. 2012).

[31] Mazoyer, J., Baudoz, P., Mas, M., Rousset, G., and Galicher, R., "Experimental parametric study of the self-coherent camera," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8442** (Sept. 2012).

[32] Mazoyer, J., Baudoz, P., Galicher, R., Mas, M., and Rousset, G., "Estimation and correction of wavefront aberrations using the self-coherent camera: laboratory results," *Astronomy and Astrophysics* **557**, A9 (Sept. 2013).

[33] Delorme, J. R., Galicher, R., Baudoz, P., Rousset, G., Mazoyer, J., and Dupuis, O., "Focal plane wavefront sensor achromatization: The multireference self-coherent camera," *Astronomy and Astrophysics* **588**, A136 (Apr. 2016).

[34] Bottom, M., Shelton, J. C., Wallace, J. K., Bartos, R., Kuhn, J., Mawet, D., Mennesson, B., Burruss, R., and Serabyn, E., "Stellar Double Coronagraph: A Multistage Coronagraphic Platform at Palomar Observatory," *Publication of the Astronomical Society of Pacific* **128**, 075003 (July 2016).