Direct Imaging of Exoplanets: Science & Techniques
Proceedings IAU Colloquium No. 200, 2005
C. Aime and F. Vakili, eds.

doi:10.1017/S1743921306009112

A simulation code for AO assisted 3D spectroscopic imaging of extrasolar planets

Alessandro Berton[1], Markus Feldt[1], Raffaele G. Gratton[2], Thomas Henning[1], Silvano Desidera[2], Stefan Hippler[1] and Massimo Turatto[2]

[1]Max-Planck-Institut für Astronomie (MPIA), Königstuhl 17, D-69117, Heidelberg, Germany
email: berton@mpia.de, feldt@mpia.de, henning@mpia.de, hippler@mpia.de.

[2]Osservatorio Astronomico di Padova INAF, Vicolo dell'Osservatorio 5, I-35122, Padova, Italy
email: gratton@pd.astro.it, desidera@pd.astro.it, turatto@pd.astro.it.

Abstract. We present here a software for simulations of observations made with an Integral Field Spectrograph attached to an extreme adaptive optics system, with the main goal of simulating direct detection of extrasolar planets and to test the capabilities in detecting planets of an instrument based on IFS on large telescopes. This code, written for IDL, has been conceived within the CHEOPS project, a second generation "Planet Finder" instrument for ESO's VLT; but it has been extended to the case of various ELTs. Here we describe in detail the procedure adopted in order to simulate realistic values of speckle noise, Adaptive Optics corrections, specific instrumental features and the efficiency of a Simultaneous Differential Imaging technique to increase the signal of the planet.

Keywords. Extrasolar Planets, Simulations, Adaptive Optics, Integral Field Spectroscopy.

1. Introduction

Direct detections of Jupiter-like extrasolar planets, with the present technology available, are still a challenging goal to achieve. Difficulties come from the complex structure of the stellar Point Spread Function (PSF), which is covering the light of the planet. This stellar halo is usually brighter than the planet, at every wavelength, and since atmospherical speckles are the most important source of noise that we have to consider in direct detections of planets (Racine *et al.* 1999), an efficient method for speckle noise reduction is required. This noise can actually be reduced in case of an AO system being able to reach very high Strehl ratios S: thus, an extreme AO system is mandatory in order to reduce dramatically the speckle intensity. But even after AO correction, the speckle noise is still orders of magnitude larger than the photon noise; therefore the reduction of the speckle noise to a level comparable to the photon noise can be achieved only using additional techniques.

A special Simultaneous Differential Imaging technique (SDI), applied to Integral Field Spectroscopy (IFS) observations of the star-planet system has been suggested within the CHEOPS project (CHaracterizing Exo-planets by Opto-infrared Polarimetry and Spectroscopy, Feldt *et al.* 2004), a project for a Planet Finder instrument on ESO's VLT. The basic idea is to use the spectral features of the planet in the near-infrared, which are in general broad molecular absorption bands (methane bands for Jupiter-like planets), in order to enhance the planetary signal, and then to subtract at the same time the light from the star and the noises related to it.

In order to test the capability of such a technique in reducing noise and detecting planets, we developed a dedicated software that simulates an observation of an extrasolar

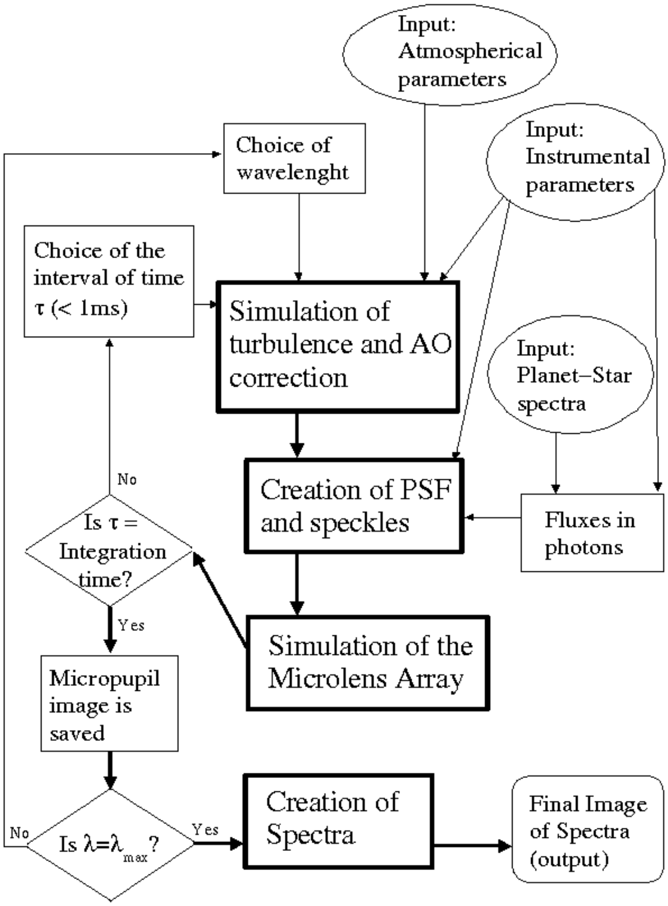

Figure 1. General flow-chart of the simulation code. Details are described in the text.

planet using an IFS. From the analysis of the results of the simulations, it has been possible to understand which kinds of planets are really detectable and characterizable for various telescope diameters, e.g. an 8m-class telescope. The code can be easily adapted to various kinds of telescopes, sites and instrumental features, in particular allowing an interesting analysis of the different results achievable with Extremely Large Telescopes (ELTs) with mirror diameters between 25 and 100 meters. Some results are presented here, and discussed more in detail in Feldt *et al.* (2005).

2. Description of the simulation code

The simulation code we are going to present here was written for IDL in the context of the CHEOPS project, and its general flow-chart is shown in Fig. 1. The IFS consists on a microlens array composed by 254×254 hexagonal lenses covering a field of view of $3''\!.5 \times 3''\!.5$. The disperser is an Amici prism, which can give spectra with constant resolution of 15 in the spectral region between 0.9 and 1.7μm. A detailed description of the CHEOPS IFS can be found in Claudi *et al.* (2004). With our simulation code we simulate accurately speckle patterns in order to estimate correctly the Speckle noise. Then, using these simulated observations we determine which kinds of planets are really detectable with such an instrument, as a function of different parameters: physical (masses,

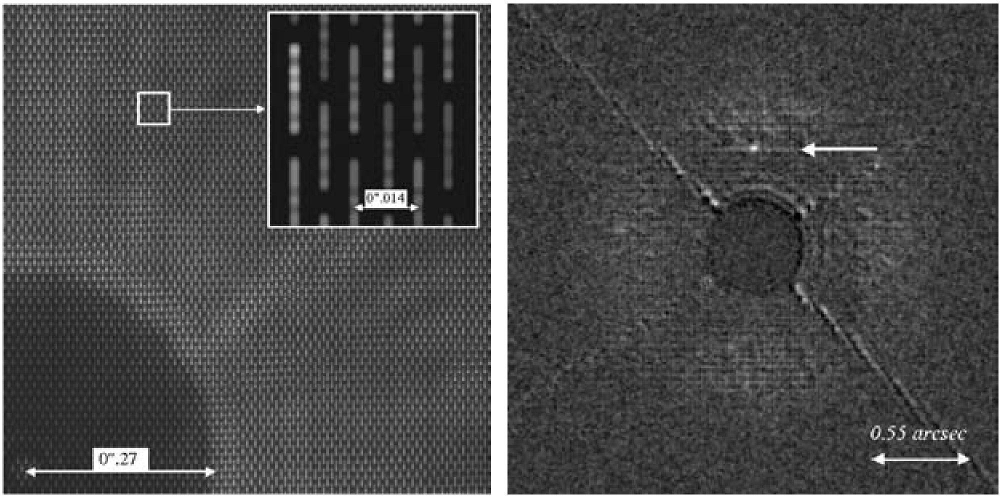

Figure 2. At left: a detail of the image of spectra obtained at the end of the procedure. The star is placed on the left-bottom corner, and it is visible the effect of a simulated coronograph. At right: the detection of a BD of 30 M_J around a 5 Gyr old star at 40 pc after the differential imaging (S/N$\sim$30).

ages, angular separations, distances), instrumental (telescope features, AO, etc.) and the atmospheric seeing conditions.

Here we summarize the main concept and results of the code, a more detailed description would be available in a forthcoming paper (Berton *et al.* 2005). The procedure starts creating an istantaneous wavefront describing the atmospheric turbulence in a specific moment of the observation (in general for a time interval shorter than a millisecond). This wavefront is at first corrected by a simulated AO system, able to reach a Strehl Ratio of 0.7 or higher in J-band; then it is combined with the pupil of the telescope. In this way an instantaneous PSF is generated, including the speckle pattern related to that specific moment. If needed, a coronograph can be introduced in simulations. The simulation of a long exposure (for planet detection several hours can be necessary) is done by combining together many instantaneous PSFs: this allows the representation of the speckle evolution with time. The result of this process is a final monochromatic PSF. The next step is the simulation of the microlens array. This is done by splitting the image in small hexagonal portions which are analyzed and focused on the disperser as micropupils. To simulate the disperser the code must repeat the entire procedure at various wavelengths to recreate the spectral structures of the PSF. This gives as a result a set of micropupil images each one for a specific resolution element, which will be combined on the detector for creating the final spectral image. An example of this final image is shown in Fig. 2 at left.

At this point, in order to apply SDI we extract the information related to specific λ from all the spectra and then we create a set of monochromatic images, each one corresponding to a given resolution element. These images can be combined in different ways, applying different mathematical operations in order to remove the stellar light (and the speckles with it). The images must be scaled in wavelength and flux before the comparison. In Fig. 2 at right the detection of a Brown Dwarf of 30M_J placed at 40pc from the Sun is shown, and it is detectable with a Signal-to-Noise ratio of 30.

3. Preliminary results

We made a complete set of simulations for an 8-meter class telescope, based on VLT, using different models of planetary systems, with different masses (between 1 and 30 M_J), ages (between 0.01 and 5 Gyr), distances (3, 10 and 40 pc), spectral type of the host star (G0V and M0V) and various angular separations, for a fixed exposure time of 4 hours. The models of the planetary spectra were taken form Burrows *et al.* (2004). In general, the speckle noise was found to be reduced of a factor around 10^{-3} by using the IFS, which makes the total noise approach to the photon noise. The results in the different cases have been expressed as signal-to-noise ratios (S/N) and plots of S/N vs. separation. The complete list of results will be presented in Berton *et al.* (2005): at the moment we present here some general conclusion about all the simulations.

First of all, an important result is that a Jupiter-like planet younger than 1Gyr, around a G0V star at 3 pc from the Sun, appears to be visible at a separation of ∼1 arcseconds from the host star after an integration time of 4 hours. This could be close to the case of the planet around ε Eridani, one of the most important targets for the new ground-based "Planet Finder" instruments which are on project now. If we go further, at 10pc, planets with masses $\geqslant 5M_J$ and ages around 1 Gyr can be clearly detected. Passing from a G0V star to an M0V star the S/N increase considerably, because of the lower contrast between star and planet.

Some simulations are ongoing at present also for some ELTs: in particular we applied our code to a 100-meter telescope basing on ESO's OWL project (OverWhelmingly Large telescope, Gilmozzi 2004). We used a model of the entrance pupil (N. Yaitskova, private communication) in order to consider all possible diffraction patterns given by spiders and segmentations of the mirrors. A similar model has been used also for a smaller 50-meter telescope. Some preliminary results are presented and discussed in Feldt *et al.* (2005).

4. Conclusion

Our simulation software is at present sophisticated and complex, and although it may need some higher order improvements, which will be done in the immediate future, it can be considered almost complete. With numerical simulations we evaluated the capabilities of an IFS instrument to reduce speckle noise. One can achieve a reduction factor of 10^{-3}, which can be considered a good result for the SDI technique. It allows the detection, even with an 8-meter telescope, of a vaste range of faint companions around stars in the solar neighbourhood. Beside detection, in case of high S/N with IFS-SDI we can extract the whole near-infrared low resolution spectrum, for a firts characterization of the planet.

References

Berton, A., Gratton, R.G., Feldt, M. *et al.* 2005, *in preparation*

Burrows, A., Sudarsky, D., & Hubeny, I. 2004, *ApJ*, 609, 407

Claudi, R.U., Turatto, M., Gratton, R.G. *et al.* 2004, in: *Ground-based Instrumentation for Astronomy, Proceeding of the SPIE*, Volume 5492, 1351-1361

Feldt, M., Henning, T., Hippler, S. *et al.* 2004, in: *Exploring the Cosmic Frontier: Astrophysical Instruments for the 21st century, ESO Astrophysics Symposia*, 17-21 May 2004, Berlin, Germany

Feldt, M., Berton, A., Henning, T. *et al.* 2005, in: *Direct Imaging of Exoplanets: Science & Techniques*, October 3-7, Nice, France. (This proceeding.)

Gilmozzi, R. 2004, in *Ground-based Telescopes, Proceeding of the SPIE*, Volume 5489, 1-10

Racine, R., Walker, G.A.H., & Nadeau, D. *et al.* 1999, *PASP*, 111, 587