# The Coronagraphs of MIRI/JWST and SPHERE/VLT as Valuable Experiences for TPF-C

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## ABSTRACT

This paper presents two projects for which we are developing advanced coronagraphic system based on phase mask coronagraphs.

## INTRODUCTION

For about 10 years, a lot of coronagraph concepts were proposed and studied theoretically by mean of numerical simulations. Some are tested in the lab in the context of TPF-C project but except the classical Lyot coronagraph only the Four Quadrant Phase Mask (FQPM, Rouan et al. 2000) was installed on a ground-based telescope (Boccaletti et al. 2004) in combination with Adaptive Optics system and has already provided scientific results (Gratadour et al. 2005, Boccaletti et al. 2007). The purpose of this paper is first of all to present some actual projects both in space and on the ground where FQPMs will be implemented to address the characterization of giant gaseous planets at near and mid IR wavelengths, and second of all to outline the importance of such developments for TPF-C.

## 1. MIR/JWST

By 2013, the James Webb Space Telescope (JWST, Gardner et al. 2006) will be the largest telescope in space to provide a large spectral coverage from visible to mid-IR wavelengths (0.6μ–25μ). JWST has a large scientific program defined in a Design Reference Mission. One of these programs is entitled “planetary systems and origins of life”. It includes the understanding of planet formation and evolution also in relation with circumstellar disks.

JWST is equipped with three instruments: NIRCAM, NIRSPEC and MIRI. The latter is the mid-IR facility of JWST and is developed in a NASA-led partnership with a European consortium sponsored by the European Space Agency (Wright et al. 2003). MIRI is composed with 2 modules one which is the imager under French responsibility (Dubreuil et al. 2003). At the Observatoire de Meudon, we are designing a coronagraph suite installed in the focal plane of the imager. The coronagraphic system is combining 3 monochromatic FQPMs for exoplanets research and characterization operating at 10.65μ, 11.40μ and 15.50μ, plus a standard Lyot coronagraph at longer wavelengths (23μ) for the study of silicates in cold circumstellar disks.

The selection of coronagraph filters was made upon the analysis of exoplanet spectral models (Allard et al. 2001) compared to the background noise. As illustrated in Figure 1 the best spectral region to search for exoplanets is located between 9μ and 15μ. At shorter wavelengths, MIRI is undersampled and at larger wavelengths the background is dominating the planets signal. The set of filter allows measuring the presence of ammonia in the planetary atmosphere, which is a good sensor of the temperature and of the sedimentation.

To address the performance of the coronagraphic system we developed numerical simulations fully described in Boccaletti et al. (2005) and Baudoz et al. (2006). We considered the JWST segmented pupil with 30μ gaps, phasing defects of about 84nm rms, mid frequencies aberrations of 58nm rms and high frequencies of 17nm rms. In our system analysis we found that most of the limitation in MIRI comes from the pupil position uncertainty (with respect to the Lyot stop) which may reached 4.5% of the pupil size, the defocus at the focal plane of JWST (±2μ) and the pointing accuracy (about 5mas). Expected performances are given in Table 1 in some particular condition. Unlike MIRI, NIRCAM is corrected for defocus and pupil position. Nevertheless, exoplanet contrasts

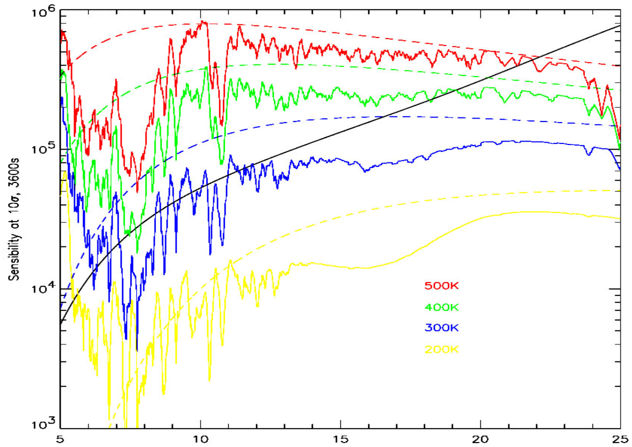


***Figure 1:*** *Spectra of exoplanets modeled by Allard et al. (2001) for several temperatures and compared to the background model for MIRI/JWST. The range between 9µ and 15µ is clearly the best place to look at. The sensitivity will allow to detect planets with temperature larger than 300K.*

***Table 1:*** *Raw contrast on the coronagraphic image for different cases (jitter is 7mas rms and pointing accuracy is 5mas).*

| **Observation conditions** | Attenuation on the peak | Contrast 1 λ/D | Contrast 3 λ/D | Contrast 6 λ/D |
|---|---|---|---|---|
| **1.5% shear + 1µ defocus** | 420 | 1392 | 4338 | 11940 |
| **3% shear + 2µ defocus** | 256 | 901 | 2912 | 9345 |
| **5% shear - 3µ defocus** | 115 | 386 | 1399 | 5016 |

are more favorable in the mid-IR, which makes MIRI and NIRCAM very complementary. In Figure 2, we give the impact of the pointing accuracy on the expected performance.

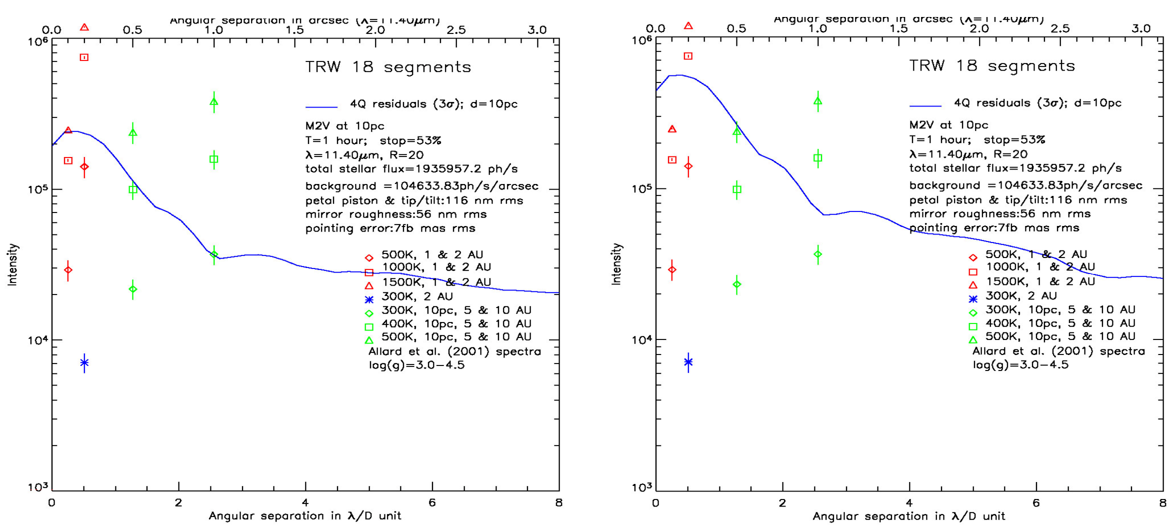


***Figure 2:*** *Achievable contrast at 3 sigma versus angular distance for 5mas pointing accuracy (left) and 10mas (right). Colored symbols are corresponding to different types of planets as indicated on the plot. The presented performance implies the calibration of the coronagraphic image residue with either a reference star or observation of the target star at a different roll angle. The degradation is about linear in between 5mas and 10mas (for comparison PSF size is 360mas at 11.4µ.*

In the mid next decade, MIRI will be the only instrument in space equipped with a specific coronagraphic system. Although several parameters are imposed by the telescope, the system analysis we made has contributed to the optimization of the coronagraph design. In this respect, this study can benefit to TPF-C at several levels:

development of phase masks for use in space in specific condition (vibration, thermal cycling, etc.); evaluation of critical issues that reduce performance (defocus, pupil positioning, etc.); experience we get in simulations and manufacturing. The requirements we put on MIRI to achieve detection of giant planets is giving a very good idea of what TPF-C would have to do in terms of stability to achieve the detection of telluric planets. Several orders of magnitude will have to be gained at many levels. The error budget will have to be controlled much better than in any previous instruments.

## 2. SPHERE/VLT

Unlike MIRI, SPHERE is a 2$^{nd}$ generation ground-based instrument at the VLT (ESO). SPHERE stands for Spectro Polarimetric High contrast Exoplanet REsearch and is probably one of the first instruments to be fully optimized for the direct detection and characterization of exoplanets. SPHERE is studied among a large European consortium including 12 institutes in several countries (France, Germany, Italy, Switzerland, Netherland). Target objects will be giant gaseous planets down to 1 Jupiter mass and will be searched for inside young stellar associations (50–150pc), nearby stars (smaller orbits), stars with known planets (from radial velocity surveys with long term residuals) and stars of intermediate age (a few 100Myrs). Detailed specifications of SPHERE can be found in Beuzit et al. (2006). The fundamental principle in this instrument is to take advantage of differential imaging whether in several spectral bands or different polarization states. For that, an AO corrected wavefront is feeding an IR coronagraphic device, which distributes the light into 2 instruments IRDIS (an IR camera using dual band imaging) and IFS an integral Field Spectrograph adapted to high contrast imaging. A dual polarization camera ZIMPOL is installed in the visible channel of the instrument with its own coronagraph.

A realistic simulation of all observing modes of the instrument is developed under CAOS environment (Carbillet et al. 2004). This tool has several goals which are :

– to put specifications on the system in terms of :
  - AO related parameters
  - PSD and amplitude of phase aberrations upstream the coronagraph
  - pointing alignment (accuracy, reproducibility)
  - pupil centering (accuracy, reproducibility)
  - focus stability
  - chromatic aberrations upstream/downstream coronagraph
  - comparison of coronagraphs and optimization of each design
  - chromaticity
  - dual imaging filter parameters
  - detector related parameters (Flat Field)
  - to assess performance in terms of astrophysical parameters (Sp, distance, age, planet mass, atmospheric model)
  - to provide inputs to the Exposure Time Calculator

In Figure 3, we give an example of system analysis concerning the impact of offset pointing which demonstrates how accurate have to be the pointing in such a system (about 0.5mas). Figure 4 shows an example of detectability for an M0V star at 40pc. High order AO system combined with advanced coronagraphs, differential imaging and smart calibrations are needed to detect 1$M_J$ young planets if specifications of system and sub-systems are met.

The originality of SPHERE is the combination of the 3 instruments to improve spectral coverage, and hence the ability to characterize exoplanets and also the chance of detection by reducing false alarms. Another peculiarity is the coronagraphic device, which actually includes several types of coronagraphs to take advantage of each concept. The main component will be an achromatic coronagraph to be used in the NIR survey (simultaneous observations with IRDIS in H and IFS in YJ). For that, we are developing prototypes of achromatic FQPM based on the use of half wave plates (Mawet et al. 2006) and Apodized Lyot coronagraph (Soummer 2005). The coronagraphic device will also include classical Lyot masks, and some achromatic coronagraphs optimized for the H and K band, whether an Apodized Lyot or a FQPM/AGPM using Zero Order Gratings (Mawet et al. 2005a,b).

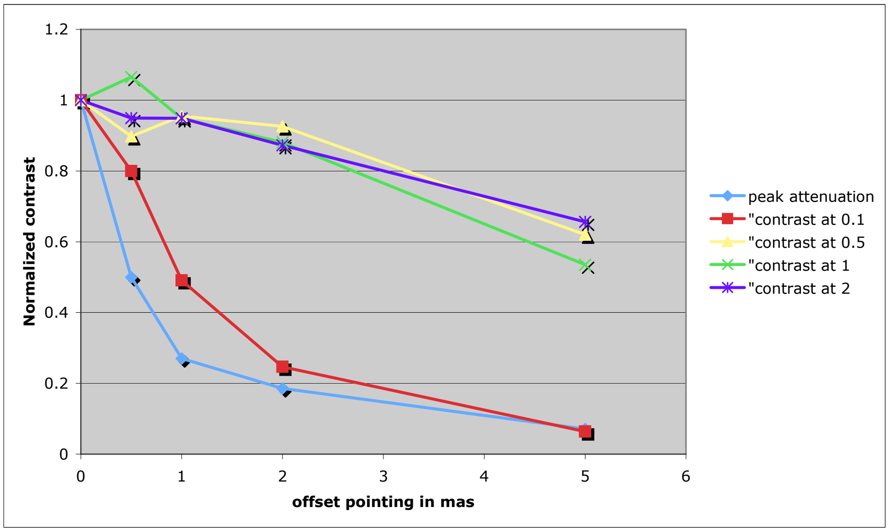


***Figure 3:*** *contrast (with differential imaging) as a function of offset pointing (in mas) at different positions in the field.*

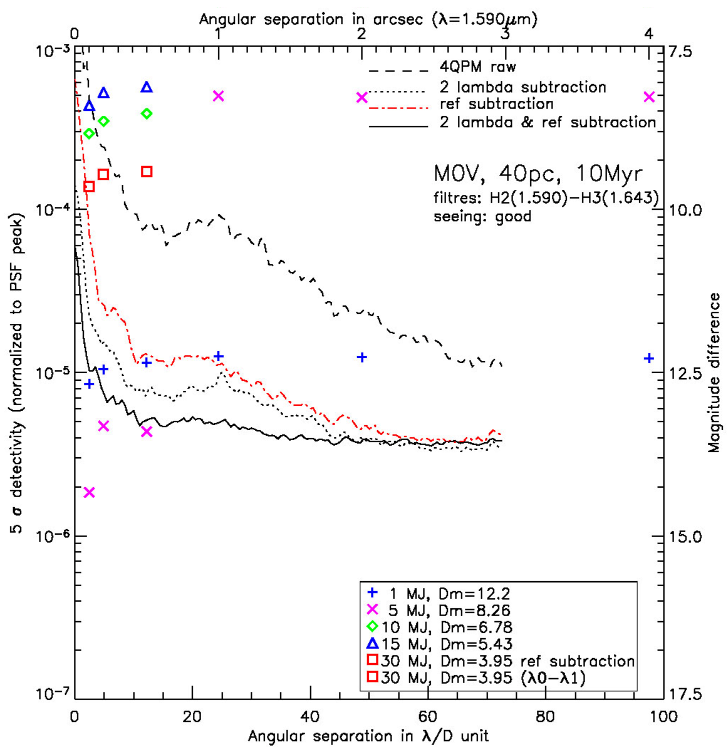


***Figure 4:*** *Contrast at 5 sigma versus angular distance for the raw coronagraphic image (dash), the differential imaging (dot) and the double differential imaging (solid). Colored symbols are corresponding to different planetary mass.*

## 3. CONCLUSIONS

Although TPF-C has a much more challenging objective than MIRI and SPHERE, this project will benefit of the many developments we made on 1/ prototyping of coronagraphs, 2/ system analysis by numerical simulations and 3/ estimation of performance for ground-based as for space telescopes not only in terms of technique but also regarding scientific aspects (input catalog for instance). The FQPM is the only high contrast coronagraph manufactured and validated in the laboratory and on the sky at several spectral bands (see Baudoz et al. this proceeding). A new system will be implemented at the VLT by Feb. 2007 to take advantage of the Simultaneous Differential Imager (Lenzen et al. 2004, Biller et al. 2005).

In what concern estimation of performance or system analysis, we have developed a very complete model of SPHERE that could be easily turned to match TPF-C requirements. To carry on this study in a TPF context, a concrete collaboration between the TPF-C team and our group is desirable, not necessarily through ESA but rather with students and postdocs.

The selection of a coronagraph for TPF-C is definitely a puzzling issue. It is obvious that inner working angle and throughput are not sufficient parameters to do the choice in such a complex program. And, at some point, a thorough simulation including all limiting factors would be needed to perform the selection on the basis of signal to noise ratio estimate.

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