SF2A 2019
P. Di Matteo, O. Creevey, A. Crida, G. Kordopatis, J. Malzac, J.-B. Marquette, M. N'Diaye, O. Venot (eds)

SPECTROIMAGING OF YOUNG PLANETS WITH ELT-HARMONI

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Abstract. HARMONI, the first-light VIS & near-IR integral field spectrograph (IFS) of the ELT, will include a high-contrast imaging mode. Thanks to the high angular resolution of the ELT, to the spectral resolution of HARMONI (R=3500-18000), and to its adaptive optics system, this mode will enable the spectral characterization of young giant planets, in particular to constrain their formation processes. By creating 10^{-6} contrast at minimum separations of 50-100mas in the H & K bands, it will make it possible to study a much larger number of planets than with the current high-contrast instruments, and thanks to the GAIA catalogue, it will help measuring their mass-luminosity relation. This contrast level assumes that classical post-processing techniques will be used, but lower contrast values could be obtained by using the high spectral resolution of HARMONI to look through the speckle noise, especially at close separation.

Keywords: exoplanets, high-contrast imaging, high spectral resolution, ELT

1 Introduction

As of mid-2019, more than 4000 planets have been detected, most of them indirectly, using the radial velocity method, or the transit method. Transmission spectroscopy can be performed during transits, but only the upper part of the atmosphere is probed (Tinetti et al. 2013), and only a small fraction of planets transit their star.

The alternative is to directly image the planets. This is difficult because of the very small separation between a star and its planets, and because of the very high flux ratio between them. Instruments like VLT-SPHERE (Beuzit et al. 2019) have been specifically designed to observe young giant planets.

The current direct imagers provide R$\sim$50 spectra in the near-IR. This is enough to roughly measure the effective temperature and the surface gravity of the planet, but determining the physics of planet formation requires to measure the relative abundances of key molecules to determine the C/O ratio, and this will require higher, R$\sim 10^4 - 10^5$, spectral resolution.

Following the suggestion of Snellen et al. (2015), the detection limit set by the speckle noise in direct imagers could be partially removed by correlating an observed spectrum observed at a sufficiently high resolution with a template spectrum (based on a single molecule, or a combination of molecules).

Recent observations highlight the high potential of IFS for direct imaging. SINFONI observations have been processed to spatially map the presence of a few molecules (H20, CH4, NH3, CO), resulting in the detection and the partial characterization of planet Beta Pictoris b in spite of a low, 20 %, Strehl (Hoeijmakers et al. 2018). MUSE observations have been processed to look for the H-α hydrogen emission line around star PDS70, resulting in the detection of planets PDS70b and c (Haffert et al. 2019). While the former has been imaged before (Keppler et al. 2018), the latter is a new detection that was not possible with photometric observations, as the planet appears to be embedded in the formation disk.

HARMONI is the first-light, AO-assisted, visible and near-IR IFS of the ELT(Thatte et al. 2016). It will provide mid to high spectral resolution datacubes in a 1" Nyquist-sampled field of view. It will address a large variety of science cases, from solar system objects to the first galaxies. This also includes the spectral characterization of exoplanets, both through transmission spectroscopy, and through direct imaging. In the latter case, a dedicated sub-system is used to perform these observations, and this paper presents it.

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2 Design of the HARMONI High Contrast Subsystem

The high-contrast (HC) imaging mode of HARMONI aims at providing the instrument with the capability to image exoplanets with a 10^{-6} contrast at 100mas from the star (goal: 70mas) from 1.45 to 2.45 μm (goal: 1.25 to 2.45 μm). As illustrated in fig 1, this would allow HARMONI to study many more young giant planets than instruments like SPHERE, and to characterize their atmosphere. The HC subsystem will rely on the single-conjugate AO subsystem (SCAO) that will provide a ∼75% Strehl ratio. Note that HARMONI also uses a laser tomographic AO subsystem (LTAO) (Neichel et al. 2016).

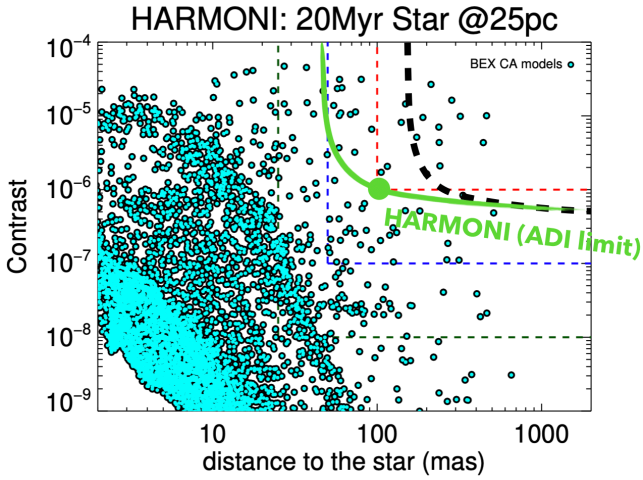

Fig. 1. Contrast separation diagram showing a simulated population of young giant planets around 25pc stars based on the Bern model (Mordasini 2014). The dashed black line represents the contrast limit of VLT-SPHERE, while the solid green line does the same for HARMONI, assuming an ADI-based post-processing of the data.

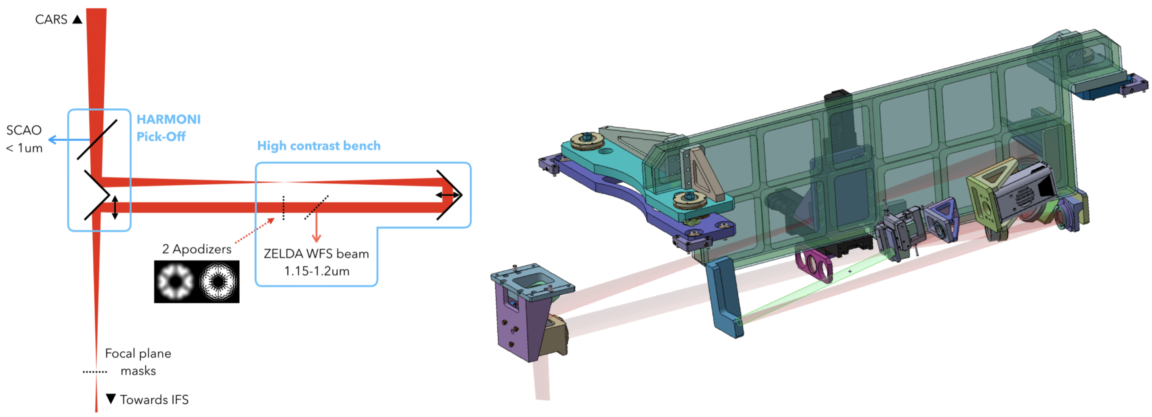

Fig. 2. Conceptual view (left) and 3D rendering (right) of the HC subsystem of HARMONI. Light is picked right after the SCAO dichroic and sent towards the HC bench where it is optically processed before being returned towards the IFS. The front facing optics are those of the Zernike wavefront sensor.

2.1 Attenuating the diffracted intensity & Monitoring the quasi-static aberrations

Like other direct imaging instruments, the HC subsystem must rely on a coronagraph to attenuate the intensity of the diffracted light, and to limit the dynamics of the PSF on the detector. Since HARMONI does not use an atmospheric dispersion corrector (ADC), and to keep the design of the HC subsystem as simple as possible, the coronagraph cannot use a focal plane mask to create contrast, like an APLC does in SPHERE. Instead, the coronagraph uses apodizers (Carlotti et al. 2011), and a focal plane mask to prevent saturating the detector.

Two apodizers will create a 10^{-6} contrast in complementary regions: from 4.5 to $11.5\lambda/D$, and from 7 to $39\lambda/D$. This translates into a 44-60mas minimum separation for the H and K bands, or, alternatively, into a 0.9-1.2 minimum AU distance for a 20pc star. The largest separation is chosen to match the SCAO angular cut-off frequency, as well as the FoV of HARMONI in its Nysquist sampling mode (4mas platescale).

As the SCAO analyses light at $\sim 0.8\mu m$, and because its optics introduce significant non-common path aberrations, a dedicated Zernike wavefront sensor(N'Diaye et al. 2013) is part of the HC subsystem. It picks light right before the apodizer, below $1.25\mu m$, and analyzes it in a narrow band centered at $1.175\mu m$. It will provide a 0.1-10 Hz monitoring of the quasi-static wavefront aberrations. Its cutoff wavelength makes it possible to observe the $1.27\mu m$ oxigen lines, as well as the $1.28\mu m$ Paschen-β line. It reimages the pupil, and this data will be used to monitor the pupil movement to control the apodizer position in an open loop.

2.2 *Opto mechanical implementation*

The HC subsystem is part of the natural guide star system (NGSS), which is located between the calibration and relay system (CARS) and the IFS. An illustration is given in fig.2. It is composed of a pick-off unit, and a vertical bench onto which the apodizer unit and the Zernike wavefront sensor are attached. The focal plane masks are located downstream, at the entrance of the cryostat. They will provide a 10^{-4} attenuation so that the star spectrophotometry and rough astrometry can be monitored during observations. Because of the absence of an HDC, the focal plane masks are asymmetric, and the minimum separation changes with the position around the star. A static ADC could be added to attenuate this effect by $\sim 60\%$ for a $z = 5 - 50$ deg zenith angle.

2.3 *Error budget*

The ability of the HC subsystem to achieve its goal will greatly depend on the surface quality of the optics of the instrument, and, in a lesser way, of the aberrations due to the telescope. An extensive Fourier optics simulation, based on PROPER (Krist 2007), has been used to estimate the surface quality of each of the optics so that the total quasi-static aberrations that they introduce does not exceed 10^{-5}. This contrast value has been chosen conservatively, assuming the final contrast, after post-processing, will be 10^{-6}.

3 Performance estimation

3.1 *Simulations*

Coronagraphic PSF have been computed while taking into account quasi-static aberrations, purely static aberrations (in particular due to missing segments and reflectivity errors of the primary mirror), and fast-changing residual atmospheric aberrations derived from the SCAO analysis (Schwartz et al. 2016). Planets are then injected in the data, using synthetic spectra, while the spectrum of the star comes from real observations. We have for instance considered the case of 51 Eri, and injected four 51 Eri b-like planets at 100, 150, 200, and 250 mas from the star, and with a 10^{-6} contrast. In addition to the photon noise, the detector RON, the sky background, and the cross-talk and the diffusion in the IFS are simulated. Various observations have been simulated, starting with low, R=3000 observations in the H+K band, to R=17000 observations in one half of the K band. We assume that observations occur over 2 to 4 hours, centered across the meridian.

3.2 *Post-processing*

3.2.1 ADI-based

Datacubes have first been processed with ANDROMEDA (Mugnier et al. 2009; Cantalloube et al. 2015), which is based on angular differential imaging. Results have been presented in Carlotti et al. (2018). They indicate that planets with a 10^{-6} contrast can be detected at 100mas, and the comparison between the injected and extracted spectra shows some differences which must be further investigated.

3.2.2 Molecular mapping

Molecular mapping has been applied on the data. After removing the star and the tellurics, a cross-correlation algorithm is applied using template spectra based on a BT-Settl model (Allard et al. 2012) that is adjusted

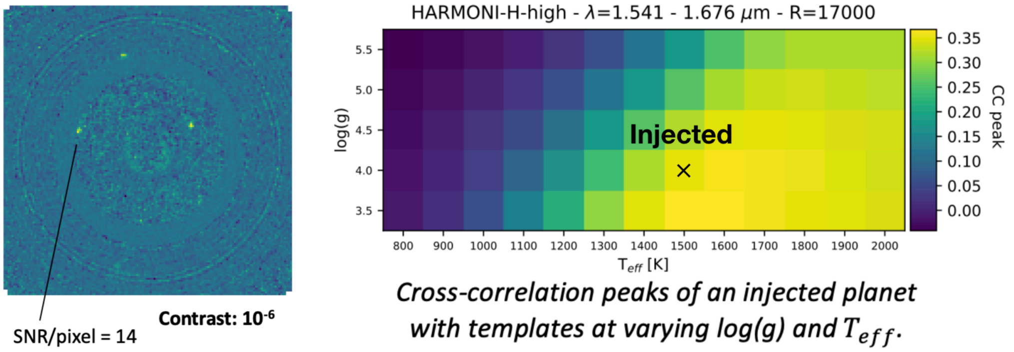

Fig. 3. Left: detection map showing planets detected at 100-250mas from the star (the 4th is in the lower part of the image). Right: Cross-correlation strength plotted as a function of the effective temperature and the $\log(g)$.

to maximize the cross-correlation peak. In the latter case, the result of this method applied to R=17000 K-band data shows that the effective temperature and the $\log(g)$ used in the injected spectra are retrieved with a precision better 200K and 0.5. A comparison to the classical ADI-based techniques will be performed in the near future, and new simulations will assess how faint a planet could be studied using this method.

4 Conclusions

The high-contrast imaging subsystem that is presented here will give HARMONI the capability to measure the relative abundances of various molecules in the atmosphere of young giant planets with a 10^{-6} contrast and located as close as 1 AU from a 20pc star. This should greatly increase the number of planets that could be studied. The high spectral resolution of HARMONI will make it possible to apply molecular mapping on coronagraphic data, which should further increase the contrast limit of the instrument.

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