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Hα IMAGING OF PROTOPLANETS WITH THE SPECTRO-INTERFEROMETER FIRST AT THE SUBARU TELESCOPE

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Abstract. The Fibered Imager foR a Single Telescope (FIRST) is a spectro-interferometer installed on the Subaru Coronagraphic Extreme Adaptice Optics platform (SCExAO) at the 8-m Subaru Telescope, Hawaï. Its capability, unique in this field, is to perform visible spectroscopy at, and even below, the diffraction limit of a monolithic telescope thanks to the fibered pupil remapping technique. FIRST has already shown its capability to resolve binary stars, and upgrades in FIRST's setup are currently being carried out in order to detect and characterize companions much fainter than their host star. In particular, a new spectrograph was designed and integrated on the FIRST replica bench at the Paris Observatory for detecting the Hα signal emitted by young exoplanets accreting matter, i.e by protoplanets.

Keywords: Spectro-Interferometry, Optical design, Pupil remapping, Single-mode fibers, High contrast imaging, High angular resolution, Protoplanets, Hα imaging, Differential phase measurements

1 Introduction

Rewarded by a Nobel prize in 2019, the discovery of the first exoplanet 51 Pegasi b orbiting a main-sequence star was announced by Mayor & Queloz (1995) and launched the investigations on a large variety of exoplanets detection methods. As opposed to indirect detection deriving the presence of a planet thanks to the host star's properties, direct detection has allowed the exoplanet's light analysis of 53 exoplanets by August 2021 (`https://exoplanets.nasa.gov/`). Thanks to direct detection and spectroscopy of the planet light, it is possible to study the formation and evolution of exoplanets, through the characterization of their surface and atmosphere, eventually searching for biological markers of life. Direct imaging is performed with high angular resolution and high dynamic instruments to detect exoplanets that are 10^5 to 10^{10} times fainter than their host star in the visible according to Seager (2010). **Direct detection by adaptive optics and coronagraphy** reaches a factor 10^7 in star-exoplanet contrast but the angular resolution is generally limited to two times the telescope's diffraction limit, i.e. roughly 100 mas with a 10-m class telescope. At a distance of 140pc, it sets the limit at a minimum of 14 UA for the separation between the star and the planet. However, from indirect radial velocity and transit methods, Fernandes & Mulders (2019) infer that the distribution of gas giant planets is maximum around 1-4 UA from the host star, i.e at an angular distance of 7-28 mas at 140 pc. **FIRST performs direct detection by interferometry, down to the diffraction limit of the Subaru Telescope, that is 16 mas at 650nm, thus reaching the region where most giant planets might orbit, inaccessible to coronagraphic methods. Its principle is based on pupil remapping and spatial filtering by single mode fibers (SMF) detailled by Perrin et al. (2006) to reach the diffraction limit by turning a telescope into an interferometer .**

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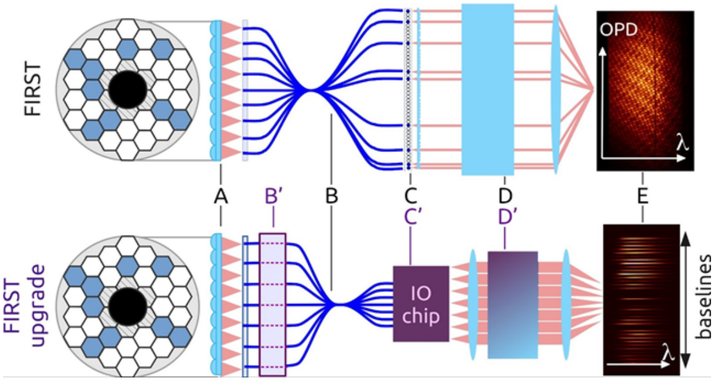
2 The FIRST instrument : Setup and on-sky results

In Hawaï, FIRST is installed at the Subaru telescope Nasmyth focus and regularly performs night sky observations. It benefits from two adaptive optics levels of correction (the AO188 and SCExAO respectively presented by Minowa et al. (2010) and Jovanovic et al. (2015)), providing a PSF with a Strehl ratio of $50-60\%$ at 750 nm. By stabilizing the wavefront and the fringes, SCExAO allows long exposures and the observation of 6.6 magnitude stars in the R band. A replica of FIRST is available at Paris Observatory in the LESIA laboratory. Fig. 1 presents the setups of FIRST version 1 (V1) and FIRST upgraded version 2 (V2) currently in development.



Top: FIRST's V1 setup. The pupil is sampled by a microlens array and subpupil fluxes are injected (**A**) into SMF (**B**). Fiber outputs are rearranged in a linear non-redundant configuration (**C**). The beams are spectrally dispersed (**D**) and recombined in a Young slits experiment way. **Bottom:** FIRST's V2 setup. Optical delay lines (**B'**) adjust optical path length differences, interferences take place into an integrated photonic chip (**C'**) for better accuracy and stability. The signal is then dispersed at higher resolution (**D'**), 2200 instead of 400.

Fig. 1.

The telescope's pupil is divided into 36 subpupils by a segmented mirror and the incident flux on each subpupil is injected into a SMF through a microlens. In FIRST V1, the remapping technique consists in arranging a set of nine fiber outputs into a non-redundant linear configuration (i.e each pair of subpupils is forming a unique baseline) and make them interfere (spatial modulation of the fringes). Only two sets of nine fibers are used for now but the whole telescope pupil could be used. As the remapping is linear, the interferometric signal can be spectrally dispersed by a prism in the orthogonal direction over the $650-900$ nm spectral band (resolving power of about 400). Until now, FIRST V1 performed closure phase measurements which reveal asymmetries in the target's intensity spatial distribution. With a contrast limited to 10^{-1}, FIRST V1 resolved and spectrally analysed the Capella binary star at the Shane Telescope of the Lick Observatory (Huby et al. 2013). In 2015, both components of the binary star Alpha Equu separated by 0.6 times the Subaru telescope diffraction limit have been detected (Huby in preparation). **FIRST V2's objective is to resolve exoplanets in addition to binary stars thanks to differential phase measurements at the Hα wavelength.**

3 A new scientific objective for FIRST : study gas giant formation mechanisms

FIRST V2's scientific objective is to understand gas giant formation process. Core accretion and gravitational instability are two formation models which differ when exoplanets are still very-young and accreting matter, i.e when they still are protoplanets ($\leq$ 4 Myrs). The first protoplanet discovered, PDS70b, has been imaged with SPHERE's extreme AO (Spectro Polarimetric High contrast Exoplanet REsearch) at the Very Large Telescope, Chile (Kepler & Benisty 2018). Haffert & Bohn (2019) confirmed the detection of PDS70b and revealed PDS70c by measuring a **signal in the $H\alpha$ line, a signature of matter accretion**, with the integral field spectrograph MUSE (Multi Unit Spectroscopic Explorer). These protoplanets are the only ones confirmed by $H\alpha$ imaging and can not constrain, validate or invalidate gas accretion mechanism in order to understand gas giant formation process. **The detection of a larger panel of protoplanets is required**. The interferometric analogue of $H\alpha$ imaging is the differential phase measurement used for example by Sturm et al. (Gravity Collaboration, 2019) to detect a gas mass orbiting the 3C273 Quasar. **$H\alpha$ differential phase measurement consists in the comparison between the measured phase at the $H\alpha$ and the continuum**. **FIRST is particularly suited to detect this $H\alpha$ signal by differential phase measurement** because it provides the capability to perform spectroscopy at an angular resolution of λ/D=17 mas at 140 pc (distance of the Taurus Molecular Cloud, the nearest star-forming region), thus probing the region where the giant planet distribution is supposed to be maximum. The contrast ratio is higher in the $H\alpha$ line region : on the order of 10^{-2} for a 1

Jupiter mass (M_{jup}) protoplanet accreting 10^{-7} M_{jup} per year. This contrast is achieved while having a 0.1° to 0.01° precision on the phase measurement reached through an increased SNR (thanks to the integrated optics chip and other upgrades) and better phase calibration (thanks to the differential phase technique). FIRST new spectrograph resolution is given by the $H\alpha$ signal width (0.3nm) and is about $656.3nm/0.3nm \approx 2200$ at the $H\alpha$ line. Table. 3 describes **FIRST instrumental upgrades needed in order to resolve protoplanets** by Hα differential phase measurements. In addition to contrast and the spectrograph's spectral resolution, the sensitivity of the instrument has to be enhanced.

	FIRST V1	**FIRST V2**
Angular resolution	8.5 mas	8.5 mas
Spectral resolution	400	2200
Sensibility in R band	6 mag	12 mag (PDS70)
Contrast	10^{-1}	10^{-2} - 10^{-3}
Measurement - Scientific target	Closure phase - Binary stars	$H\alpha$ differential phase - Protoplanets

Table 1. FIRST V1 performances & FIRST V2 instrumental upgrades

4 Optical design and performances of the R2200 spectrograph

The spectrograph is characterized by its spectral resolving power $R = \lambda/\delta\lambda$ which reflects its capability to resolve two wavelengths λ et $\lambda + \delta\lambda$ with $\delta\lambda$ the spectral resolution element. As the resolving power specification is 2200 at 656.3 nm (Hα), FIRST V1 prism is replaced by a grating in the FIRST V2 spectrograph design. The setup of the spectrograph comprises a source, a collimator, a grating, an imager and a camera. The spectrograph **source** is the V-groove in which are placed the **photonic chip fiber outputs**. The V-groove pitch is $p_{vg} = 127\mu m$, $N_s = 36$ fiber outputs are available and the fiber's numerical aperture is $NA_f = 0.12$. The total field is $y_0 = 4.45mm$. **The selected collimator is a Thorlabs 2x apochromatic microscope objective** TL2X SAP with a numerical aperture of $NA_o = 0.1$ (leading to a flux loss of about 10-15%) and a focal length $f'_{coll} = 100mm$. A **birefringent Wollaston prism** of separation $10' = 0.17°$ separates the two orthogonal linear polarisations in the X direction, as shown in Fig. 2, to avoid fringe blurring. The spectral band imaged is $\Delta\lambda = 783nm - 623nm = 260nm$ and is centered on $703nm$. The selected grating meets three specifications ; its diffraction efficiency η is maximal around the $H\alpha$ line (S1), η slightly depends on polarisation (S2) and is higher than 60% over the entire spectral band (S3). A **Volume Phase Holographic grating (VPH) with** 600 $lines/mm$ from Wasatch Photonic was chosen for the new spectrograph. This grating works in transmission and diffracts in the $m = 1$ mode. It offers higher diffraction efficiency maximum and stability over the spectral band and polarization. The imager's focal length depends on L, the detector's size in the dispersion direction and on $\alpha_{\lambda_{min}}$ and $\alpha_{\lambda_{max}}$, the incidence angles on the imager of two collimated beams associated with the extreme wavelengths of the spectral band ($623nm$ and $783nm$): $f'_{im} = L/(\tan\alpha_{\lambda_{min}} + \tan\alpha_{\lambda_{max}}) = 83mm$. **The imager choice was done thanks to the optical design software Zemax Optic Studio.** To reach the resolution of 2200 at $656.3nm$, the PSF RMS radius at this wavelength must be about $15\mu m$. A unique achromatic doublet of focal f'_{im} focuses the beam too rapidly so that the PSF radius remains too wide. The incident beam diameter on the imager is about $D = 30mm$ inducing that the numerical aperture of the imager has to be around $NA_i = \frac{1}{2*(83/30)} = 0.18$, which is small. **Two achromatic doublets arranged in a Lister configuration** (which compensates aberrations for low $NA \sim 0.25$) slowly focus the beams as the power of the doublets are reduced ($f'_{im1} = 150mm$ for the first doublet and $f'_{im1} = 80mm$ for the second). The camera for the spectrograph integration at the Paris Observatory is a **Andor Zyla sCMOS** with 2560*2160 pixels of $6.5\mu m$.**The resolving power is limited by the PSF RMS size.** Fig. 2 presents the spots diagram obtained on Zemax for different fibers in the V-groove. The resolving power is directly computed by a macro coded in Zemax. The resolving power is $R(\lambda) = \frac{\lambda}{s(\lambda)*FWHM(\lambda)}$ with $FWHM(\lambda)$ the spot diagram RMS diameter in the direction of dispersion (about $15\mu m$ at 656.3nm), $y(\lambda)$ is the ray position on the detector and $s(\lambda) = \frac{\delta\lambda}{\delta y}(\lambda)$ is the spectral dispersion in pm/μm. **The pixel size** px **and the Shannon criterion (two pixels are at least needed to sample one spot) also constrain the resolving power**. If $FWHM(\lambda)$ is smaller than two pixels, the spectrum is under-sampled. The resolving power is then computed with $FWHM(\lambda) = 2 * px$. Fig. 2 shows that with $px = 6.5\mu m$ the resolving power is 2210 at $656.3nm$. The camera at the Subaru telescope has a pixel size of $16\mu m$ for now, so with the same spectrograph, the resolving power will be limited to 1040.

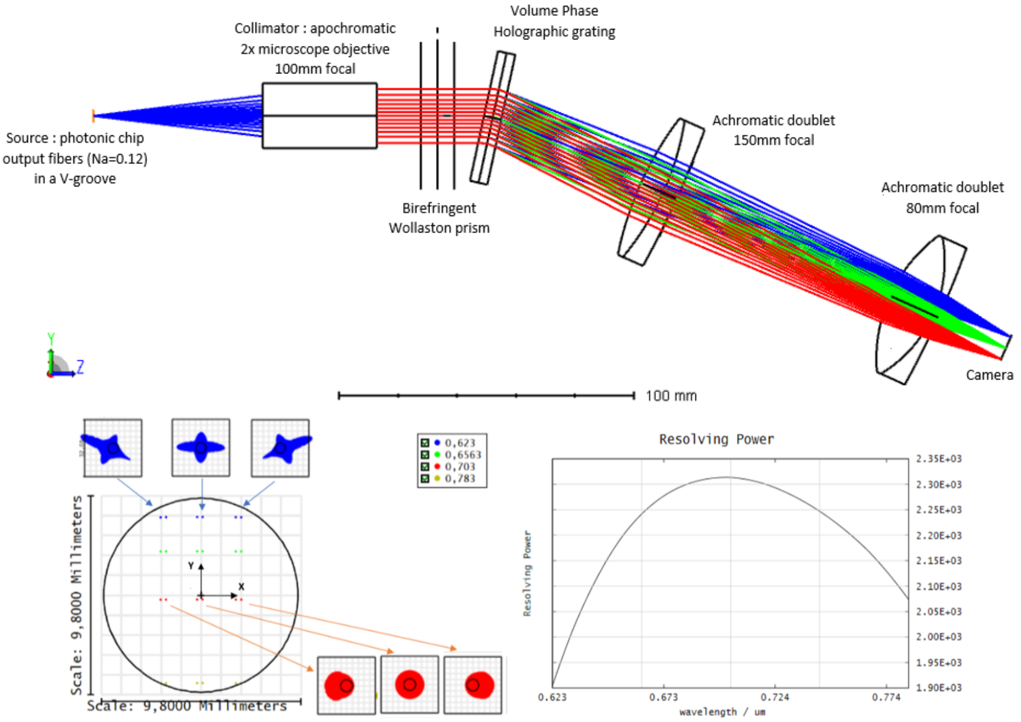


Fig. 2. Top: Optical design of FIRST new R2200 spectrograph on Zemax Optic Studio. **Left:** Spectrum positions on the detector for three fibers: at the v-groove ends and in the middle (X axis). Each fiber output produces two spectra, one for each linear polarization. The spectral dispersion follows the Y direction. **Right:** Resolving power as a function of wavelength (2210 @ 656.3nm) computed in Zemax according to the spot diagram RMS diameter.

5 Conclusions

This optical design of FIRST's new spectrograph meets the specification of a 2200 resolving power at the $H\alpha$ line with a 6.5μm pixel size and will allow the the measurement of the $H\alpha$ signal indicative of protoplanets' accretion phase. In August 2021, the spectrograph was integrated to the FIRST laboratory bench at Paris Observatory reaching a resolution of 3200 at the $H\alpha$ line. We think the alignement favoured smaller spots in the $H\alpha$ line, thus leading to a higher resolving power. Once the new setup is fully validated on laboratory data, it will be integrated to the FIRST instrument at the Subaru Telescope.

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References

Fernandes, R. B. & Mulders, G. D. 2019, ApJ, 874

Haffert, S. Y. & Bohn, A. J. 2019, A&A, 3, 749

Huby, E., Duchêne, G., Perrin, G., Marchis, F., & Lacour, S. 2013, A&A, 560

Jovanovic, N., Martinache, F., Guyon, O., et al. 2015, Publications of the Astronomical Society of the Pacific, 127, 890

Kepler, M. & Benisty, M. 2018, A&A, 617

Mayor, M. & Queloz, D. 1995, Nature, 378, 355

Minowa, Y., Hayano, Y., Oya, S., et al. 2010, in Adaptive Optics Systems II, Vol. 7736, International Society for Optics and Photonics, 77363N

Perrin, G., Lacour, S., Woillez, J., & Thiébaut, E. 2006, Monthly Notices of the Royal Astronomical Society, 373, 747

Seager, S. 2010, Exoplanet atmospheres (Princeton University Press)

Sturm, E., Dexter, J., & Pfuhl, O. Gravity Collaboration, 2019, A&A, 563, 657