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The potential of Hα spectro-astrometry to detect forming planets in disks around young stars.

I. Mendigutía[1]

[1] Centro de Astrobiología (CSIC-INTA), Departamento de Astrofísica, ESA-ESAC Campus, PO Box 78, 28691 Villanueva de la Cañada, Madrid, Spain

Abstract

This proceedings paper discusses how spectro-astrometry in Hα can be used as an alternative technique to detect planets in formation around young stars. The basic principles, methodology, and observational constraints in terms of brightness contrast, angular accuracy and signal to noise ratio are summarized, along with the specific capability of spectro-astrometry to eventually separate the individual spectra of a system formed by a young star plus an accreting planet. The case of LkCa 15 serves to illustrate the first use of spectro-astrometry to accurately test the presence of a forming planet in a protoplanetary disk.

1 Introduction

Thousands of exoplanets orbiting stars different than our Sun have been confirmed to date. However, the vast majority of them are found around relatively evolved stars, and only a few candidates have been proposed to be located in the places they form: the inner $\sim$ 100 au within the protoplanetary disks that surround the stars when these are young ($<$ 10 Myr).

Current detection methods of young planets in orbits between 1 and 100 au are mainly based on high-contrast, high-angular resolution techniques like interferometry, sparse aperture masking, or differential imaging [13, 18, 10]. However, these techniques rely on complex, state of the art instrumentation and data reduction processes, which is partially leading to a debate on the interpretation and real origin of the detections [19, 7, 15, 11, 9]. Moreover, among the few young candidate planets only two have been reported to be in the actual formation phase, based on the detection of Hα emission associated to active accretion of the circumplanetary material. The first one was reported around LkCa 15 [16], although the infrared (IR) brightness originally associated to planet emission is now attributed to persistent structures in the inner disk [19]. The second accreting planet has been reported very recently around PDS 70 [20].

Complementary observational methods are thus useful to test the presence of planets in formation and eventually provide new detections from alternative approaches. Sect. 2 shows the potential of Hα spectro-astrometry to detect such planets (for more general spectro-astrometric reviews see [1, 23, 6]), Sect. 3 provides an example of spectro-astrometry applied to LkCa 15, and Sect. 4 summarizes the main conclusions.

2 Hα spectro-astrometry and planet detection

The simplest instrumental requirement to carry out spectro-astrometry is a spectrograph with an orientable long-slit, providing 2D spectra with the dispersion axis perpendicular to the slit and the spatial axis in the parallel direction. The spectro-astrometric methodology is summarized in Fig. 1. The blue plane represents the CCD with the dispersion (λ) and the spatial (x) axes perpendicular to each other. The number of counts per second is represented by the I-axis perpendicular to the detector. The usual "intensity spectrum" is the representation of I vs λ. Spectro-astrometry also exploits the spatial information contained in the CCD by fitting the spatial profile at each wavelength, normally by means of a Gaussian characterized by its centre and full width half maximum (FWHM). Therefore, the spectro-astrometric observables include, apart from the intensity spectrum, a "position spectrum" (x_c vs λ) and a "full width half maximum spectrum" (FWHM vs λ). The position spectrum contains information about the wavelength-dependent photocentre of the emitting source in the direction of the slit, and the FWHM spectrum about the wavelength-dependent emitting size in such direction (apart from the seeing for Earth-based telescopes and the instrumental point spread function, both roughly constant for a small wavelength range). For a given target, the typical spectro-astrometric observing strategy requires two slit positions perpendicular to each other, plus two slit orientations per position (parallel and anti-parallel). The former serve to constrain the position and extent of the different sub-structures in the plane of the sky from photocentre displacements and FWHM signals, and the latter serve to address possible instrumental artifacts (real photocentre features from the sources will reverse, whereas instrumental effects remain the same, and can be removed; [1]).

Using this clever and relatively simple technique, it is possible to probe structures at angular scales of (sub-)mas [22], even with mid-size telescopes non-assisted by adaptive optics (Sect. 3). Particularly relevant for the scope of this paper is that spectro-astrometry has demonstrated to be a key technique to test the presence and find new stellar companions around young T-Tauri and Herbig Ae/Be stars, when the contrast between the corresponding Hα emission lines is different than in the continuum [2, 17, 4, 21]. The situation is similar for a system formed by a young star and a forming planet. Although these are faint and the optical continuum is clearly dominated by the central star, planets in formation are accreting their circumplanetary material and thus they probably show strong Hα emission that significantly reduces the contrast at these specific wavelengths [24].

By definition, the photocentre shift expected for a young star and a forming planet

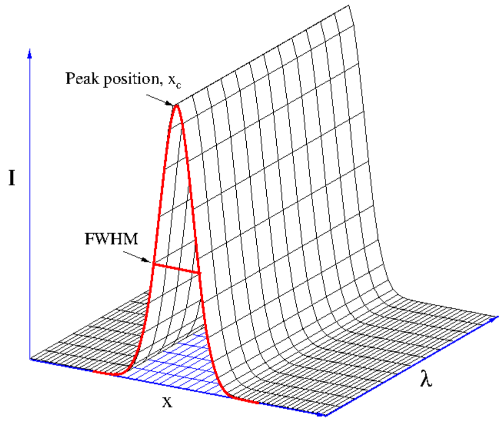

Figure 1: (Taken from [3]) The blue plane represents the CCD, with the spectral and spatial axis indicated by λ and x, respectively. The vertical, I-axis represents the intensity. For each wavelength λ, the spatial distribution in the x-axis is fitted to a Gaussian characterized its centre (x_c) and FWHM. The spectro-astrometric observables are the intensity (I vs λ), position (x_c vs λ) and FWHM (FWHM vs λ) spectra.

separated s mas in the plane of the sky and with an Hα contrast of $c_{H\alpha}$ magnitudes is:

$$\delta_{\rm phot} = \frac{I_p \times s}{I_* + I_p} = \frac{s}{10^{0.4 c_{H\alpha}} + 1}, \tag{1}$$

where I_* and I_p are the Hα intensities of the central star and the planet, and the zero-point is the photocentre position of the adjacent continuum mainly coming from the star. In turn, the accuracy needed to detect such a photocentre shift is mainly determined by the atmospheric seeing and the signal to noise ratio (SNR) of the spectra [6]:

$$\delta_{\rm phot} \sim 0.4 \times \frac{\rm seeing}{\rm SNR}. \tag{2}$$

Based on the two previous equations, Fig. 2 shows the expected photocentre shifts (left) and the nominal SNRs (right) necessary to make spectro-astrometric detections for different Hα contrasts and a range of star-planet separations. A distance of 140 pc (the rough average to Taurus) has been adopted, as well as two limits representing good and bad seeing conditions (0.6" and 1.5", respectively). These estimates show that (sub-)mas photocentre shifts are expected for accreting planets located between 1 and 100 au from the star with Hα contrasts between 4 and 9 magnitudes. Those shifts can be measured under good seeing conditions and maximum spectral SNRs arbitrarily set to 1500. For worse seeing conditions the sensitivity can decrease by up to 1 magnitude. Reaching high SNRs depends on the R-band brightness and can require co-adding individual spectra of faint stars, for which one can take advantage of the spectro-astrometric observing strategy previously mentioned.

The discussion above does not consider other aspects that are also important for spectro-astrometry. For instance, based on Hα spectra of wide-orbit sub-stellar mass ob-

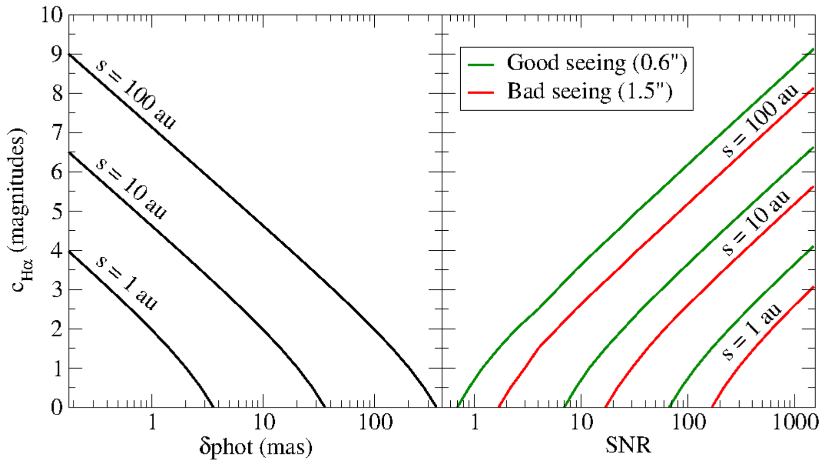

Figure 2: Star-planet Hα contrast reached as a funtion of the photocentre shift (left) and the corresponding spectral SNR (right) for different star-planet separations (at the Taurus distance of 140 pc) and seeing conditions, as indicated.

jects [5], a minimum spectral resolution of $\lambda/\delta\lambda > 1000$ is in principle necessary to resolve the spectral lines and detect planetary photocentre shifts. Indeed, higher resolution spectra are desirable to apply spectral binning and significantly improve the spectro-astrometric accuracy without losing the shape of the Hα emission. In addition, CCDs with small plate scales (in "/pixel) provide better accuracy when spectro-astrometric signals, measured in pixels, are converted into angular units.

Finally, the high angular resolution and brightness contrast that can be probed through spectro-astrometry are not the only advantages of this technique. Probably the most relevant characteristic is that spectro-astrometry is potentially capable of recovering the individual spectra of the star and the planet from the unresolved, total observed spectra $I(\lambda) = I_*(\lambda) + I_p(\lambda)$. In the simplest approach, Eq. 1 implies

$$I_p(\lambda) = I(\lambda) \times \frac{\delta_{\rm phot}(\lambda)}{s}; I_*(\lambda) = I(\lambda) \times (1 - \frac{\delta_{\rm phot}(\lambda)}{s}), \tag{3}$$

which requires knowing the star-planet separation from complementary methodologies [1, 8]. Moreover, the individual spectra in a binary system can also be deconvolved from the three spectro-astrometric observables, $I(\lambda)$, δphot(λ), and FWHM(λ), without a priori knowledge of the position of the companion [14, 21]. The eventual extraction of the Hα emission spectrum of a planet from spectro-astrometry, combined with detailed accretion modelling [24], can be a unique tool to understand the accreting phase of planets in formation.

3 A pilot study: LkCa 15

The first Hα emission attributed to a forming planet was observed around the young T-Tauri star LkCa 15 [16]. This and two more candidate planets in orbits of ∼ 15 au around the same

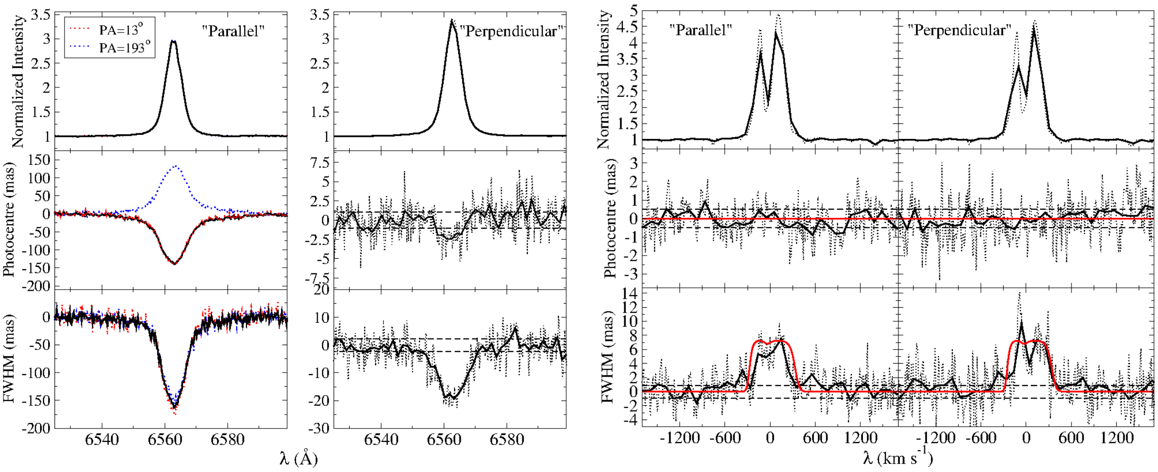

Figure 3: (Adapted from [12]) Spectro-astrometric spectra of GU CMa (left panels) and LkCa 15 (right panels). For GU CMa, the left sub-panels plot the individual spectra for the two slit orientations parallel to the position of the companion (red and blue) and the averaged spectra (black). For the perpendicular position of GU CMa, and for LkCa 15, only the averaged spectra are shown both with the original spectral resolution (dotted lines) and after rebinning (solid lines). The rebinned accuracies are indicated with the horizontal dashed lines, reaching less than 1 mas for LkCa 15. The red lines result from a model of symmetric Hα emission with extent similar to the orbit initially attributed to a planet.

star appeared bright also in the IR. A more recent work by [19] shows that the IR-bright sources could instead be part of the inner disk that extends up to $\sim$ 30 au, although the Hα emission would remain unexplained. We have recently applied Hα spectro-astrometry to LkCa 15 [12]. We first observed the well known young binary star GU CMa to test the spectro-astrometric performance of ISIS mounted on the 4.2m William Herschel Telescope. The main results are shown in Fig. 3, which serves to illustrate different topics mentioned in this work. The observed position and FWHM spectra of GU CMa are consistent with a binary system with similar continuum brightness and Hα emission dominated by the central star. In turn, the lack of photocentre shift and the similar FWHM signatures at both slit positions cannot be explained by an accreting planet around LkCa 15, but by a roughly symmetric Hα emission with size comparable to the orbit originally associated to that planet. The origin of such an extended emission is perhaps related to a variable disk wind [12].

Although our data are not consistent with the presence of an accreting planet in the case of LkCa 15, they show for the first time that spectro-astrometry can reach enough brightness contrast and spatial resolution to test the presence of forming planets in disks around young stars and look for new candidates.

4 Conclusions

Spectro-astrometry is capable of reaching an Hα brightness contrast of several magnitudes within the inner 100 au of protoplanetary disks by measuring (sub-)mas photocentre shifts. This property, along with the fact that spectro-astrometry is technically capable of extracting the Hα emission spectrum of a forming planet, makes it ideal for future surveys that allow us to increase the sample of such planets and understand their formation process.

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