Formation, Detection, and Characterization of Extrasolar Habitable Planets
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Study of the HARPS Line Profile Using a Laser Frequency Comb

F. Zhao[1,2,3], G. Lo Curto[1], L. Pasquini[1] and G. Zhao[2]

[1]European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748
Garching bei Munchen, German,
email: fzhao@eso.org

[2]Key Laboratory of Optical Astronomy, National Astronomical Observatories,
Chinese Academy of Sciences, Beijing 100012, China.

[3]Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract. High precision spectroscopy is one of the most successful methods to detect extra-solar planets. To enable the detection of Earth-like planets in the habitable zone, extremely precise instruments are required. Our lack of knowledge of the instrument line profile, non-linearity and charge transfer efficiency effects in the detector limits the achievable precision of an instrument. We report our studies on the HARPS (High Accuracy Radial- velocity Planet Searcher) line profiles, measured using the unresolved lines of a Laser Frequency Comb (LFC). We show how the line profile changes as a function of position and signal, and estimate the errors made in the line centroid measurement due to the variation of the line profile.

Keywords. HARPS, laser frequency comb, radial velocity, line profile

1. Introduction

Since the first extrasolar planet orbiting a solar-type star has been found in 1995 (Mayor & Queloz, 1995), a multitude of successful milestones have been achieved both in observation and technology for pursuing the Earth twins in the habitable zone. At present more than 980 exoplanets have been discovered, most of them via the radial velocity technique. HARPS (High Accuracy Radial- velocity Planet Searcher) represents the state of the art when it comes to radial velocity measurements, and permitted many exceptional discoveries, the most recent of which is the detection of an Earth-mass planet orbiting one star in the closest stellar system: α Cen Bb (Dumusque *et al.* 2012). The addition of a Laser Frequency Comb (LFC) calibration system will add the capability to detect super-Earth planets orbiting the habitable zone of solar-type stars.

In this work we focus on studying the shape of the line profile and its variations. We use the unresolved lines of the LFC on HARPS merely to test the instrument line profile, as we are not aiming at measuring the LFC-HARPS system stability, and for such results we address the reader to the recent work of T. Wilken and collaborators (Wilken *et al.*, 2012).

2. Shape of the line profile

We have studied the shape of the line profile after the spectral extraction and tested several functions. In some cases we have used the multiplication by the error function (erf) to force an asymmetry on the shape. Via χ^2 minimization and F-test we have found that the function which better describes the line profile is a combination of two

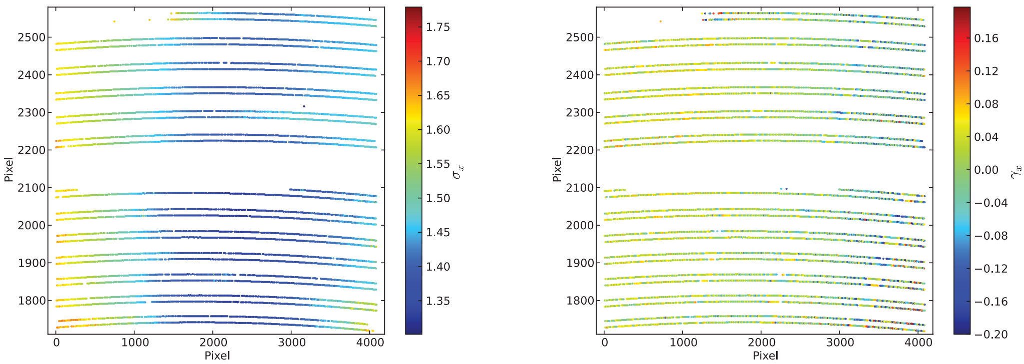

Figure 1. A portion of a well illuminated comb spectrum. Each point is an individual comb line. The right panel shows the second moment and the left shows the third moment across the detector. The main dispersion direction is horizontal, and the serial register of the CCD is on the right side of the images.(The average σ of the HARPS line profile is 1.5.)

constrained gaussians. We define a main Gaussian (A_1, μ_1, σ_1) and a satellite Gaussian (A_2, μ_2, σ_2) function, with amplitudes $A_1 > A_2$, $\mid \mu_1 - \mu_2 \mid < \max(\sigma_1, \sigma_2)$, and $1 < \sigma_1 < 2$.

3. Variations of the line profile

We use simple moment analysis to characterize the line shapes. The first moment gives the line position, the second moment produces an indicator of the line width and we use the third moment, or skewness, as an estimate of the line asymmetry. The two questions we want to address are: a) How does the line profile varies through the detector? b) Does the average line profile varies as a function of the signal ?

3.1. *Position dependence of the line profile*

We feed both HARPS fibers with the light from the LFC, and explore how the line profile depends on the position of the line in the detector. For each individual line we define a region of the detector around where we perform our analysis. The amplitude of this region is defined via a σ clipping algorithm. The background is evaluated within each region and subtracted. The variation of the second moment across the detector (Figure 1. left panel) is simply a projection effect on the flat CCD surface. The third moment (or skewness) also varies across the detector, changing from the side far from the CCD's readout towards the side close to it, which can be seen as a consequence of a combination of detector effects (possibly Charge Transfer Efficiency, or CTE, and of the spectrograph optics Figure 1. right panel).

3.2. *Line shape dependence on the measured signal.*

Another contribution to the variation of the line profile comes from the measured signal. When changing the intensity level by means of an absorber (neutral density filter), the profile of the lines is changing as well. This variation cannot be linked to the optics, nor to the source, as the observing conditions are the same for all the acquisitions. We suppose this variation originates from detector effects such as CTE. As the effect of CTE depends on the number of transfers of the charges to the serial register, we compare the average line profiles of the lines close (only few transfers) and the lines far from it. In the left panel of Figure 2, we show the difference between the average third momenta computed in the half of the detector near the serial register and the half far from it. This difference is changing with the attenuation of the signal in a way consistent with

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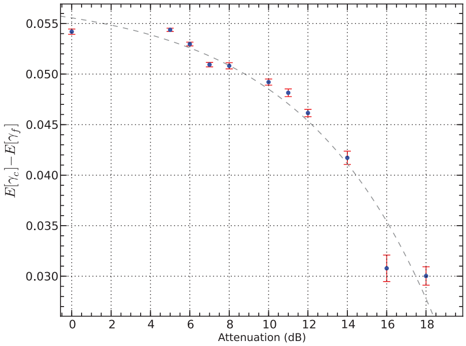

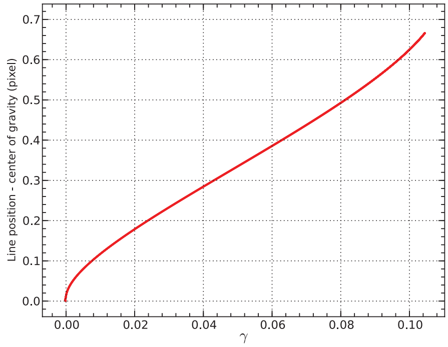

Figure 2. The variation of the line profile with the attenuation of the signal (left panel) and the relationship between the third moment (skewness) and the deviation of the center of gravity estimate from the line position (right panel).

CTE. We should note that other effects might also be at play, such as non-linearity etc., however we cannot discriminate among them with only the current data. The main result of this test is that the line profile changes with the number of measured electrons.

4. Line asymmetry and line position

We use a simulation to attempt an estimate of the error on the line position made using a center of gravity in presence of asymmetric lines. In the simulation we have assumed Gaussian lines with the typical line width that we measured on HARPS and we deformed them via an extreme CTE-like effect. The correlation between the third moment and the deviation from the line position estimated via center of gravity is shown in the right panel of Figure 2. This simulation demonstrates the magnitude of the effect and suggests a possible approach to correct the CTE-like effects, using a curve like the one in the right panel of Figure 2 to calibrate this effect.

5. Conclusions

The shape of the line profile on HARPS changes with the position in the detector and with the intensity of the lines, and is generally asymmetric. Fitting a symmetric function (Gaussian) or even using the center of gravity to measure the position of the line center may introduce an error of several m/s on the individual line. The variation of the line profile across the detector on a given spectrum is dominated by the spectrograph's optics, however, when studying lines of different intensity, detector effects come into play. When aiming for top radial velocity precision (cm s^{-1}), it is critical to account for the line shape and its variations. With this work we have characterized these variations and we have suggested a strategy to correct at least partially their effect.

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