Revealing bio-lines of exoplanets by Fourier spectroscopy

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ABSTRACT

Earth-like extra-solar planets have luminosities which are many orders of magnitude less than those of their parent star. We propose and test a method for identifying molecular spectral bands in light from such a planet by looking at an off-center part of an infrared Fourier transform interferogram. This results in superior sensitivity to narrow spectral bands, which are expected in the planet's spectrum, but are absent in the parent star. We support this by stronomical observations to illustrate the method in the visible. The results suggest that this method is applicable to searches for planet bio-lines, and for differentiating between narrow lines and wide lines in other astronomical scenarios.

Keywords: Exoplanets, habitable zone, Fourier spectroscopy, astrobiology

1. INTRODUCTION

There is a huge intensity contrast between an Earth-like extra-solar planet (exo-earth) and a parent star (typical sun-like). This enormous difference is an obstacle for imaging and spectroscopic analysis of a distant light source observed on the ground. We suggest a method of using selected parts of a Fourier interferogram of the combined light sources (both planet and sun) in order to increase the signal to noise ratio, or planet to star ratio, and identify the specific spectral features of the planet, by reducing the background due to the parent star[1,2].

An exo-earth is expected to reflect and emit a luminosity which is many orders of magnitude less than that of the parent star. However, there are special spectral features where the contrast is not so high, and luckily these are related to life-related molecules. It so turns out that the narrow molecular spectral bands from such a planet are very different from the stellar spectral lines. This can result in superior sensitivity to narrow spectral bands, which are expected in the planet

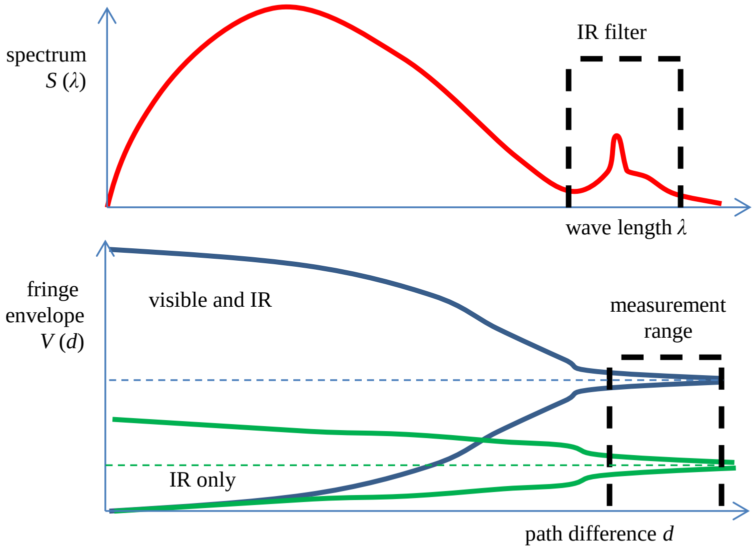

Figure 1. The principle of the observation, showing the spectrum and below its Fourier transform (the fringes envelope). The black-body spectra of the star and planet exhibit fringes at low frequencies (short path difference, not measured), whereas narrow lines are at higher frequencies. A filter letting through only the infra-red (IR) reduces even further the background. The signal to noise ratio is equal to the height of the envelope compared to its mean (broken lines), and improves when blocking the shorter wave lengths.

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spectrum, but are absent in the parent star. Thus we employ a Fourier spectrometer, which enables us to ignore fringes at short delays (low frequencies, corresponding to wide spectral lines), while measuring fringes only at longer path differences, which are sensitive to higher frequencies, namely narrow spectral lines (Fig. 1). Further reduction of the Fourier background is achieved by blocking the visible part of the spectrum, where no narrow exoearth lines are expected. Partially-scanned interferometry was developed long ago[3] and has been implemented in other observational applications such as the WINDII satellite[4] and the IASI satellite which is using the same method exactly to measure atmospheric CO_2 lines with partial path scanning interferometry (PSI) in time[5].

We supported this idea by simulations which include photon and thermal noise, and showed it to be feasible at a luminosity ratio of one part in a million in the infra-red for a Sun-like star and an Earth-like planet. We carried out laboratory experiments that mimic the scenario presented using two light sources. The first was a black body lamp representing a Sun like star and the second was a lamp with a complex spectral distribution representing the Earth-like planet. By dimming the second lamp compared to the first one, we easily managed to recreate the conditions for fifty parts in a million between the sources and to extract the faint complex signal from the spectrum obtained. Details can be found in our previous publications[1,2].

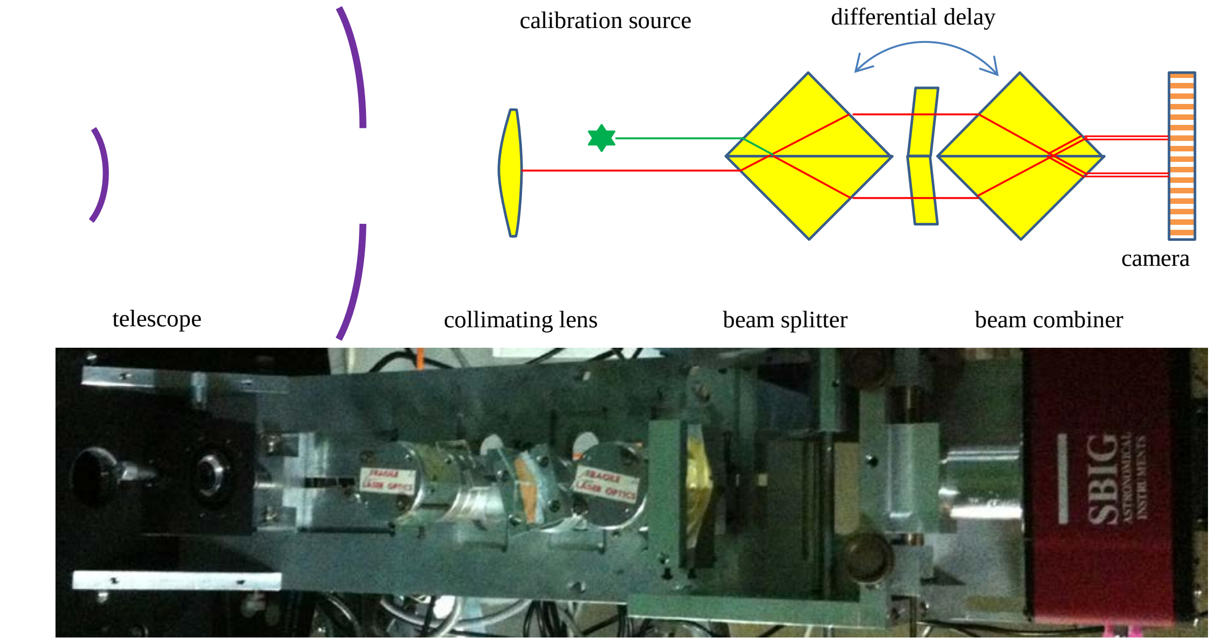

Figure 2. A schematic description and picture of the zero shear interferometer at the telescope. A collimated beam is split into two and again into two, by two consecutive beam splitters. The four images of the aperture fall on the camera, in the two complementary outputs of the interferometer. Path difference is added by rotation of two tilted glass plates from their symmetrical position, and an angle between the beams is affected by a slight rotation of either beam splitter. These two rotations set the location of the zeroth fringe, and the fringe density. The calibration source is fed at the second input port of the device. In the picture, the beam splitters have stickers on them, and we also see a final relay lens before the camera.

2. OBSERVATIONS

In order to test the idea in the astronomical context, we carried out observations on a 1 m telescope, at the Wise observatory in the Israeli desert. Not being equipped or fit to infra-red observations, we performed similar tests in the visible, to see how well we can discern narrow spectral lines. To this end we employed a zero-shear interferometer[6-8], where we had both outputs (all four beams) available to the camera (Figs. 2, 3). As such, it is a parallel (non-sequential) Fourier spectrometer, where we could take our measurements far from the zero-path difference (Fig. 4). This automatically filters out wide-band features, leaving us with only the narrowest lines. The spectrometer is a zero-shear interferometer with a tilt between the beams, leading to variable path difference across the imaging detector. Wave length calibration was performed with a LED and metal-halide lamp lines.

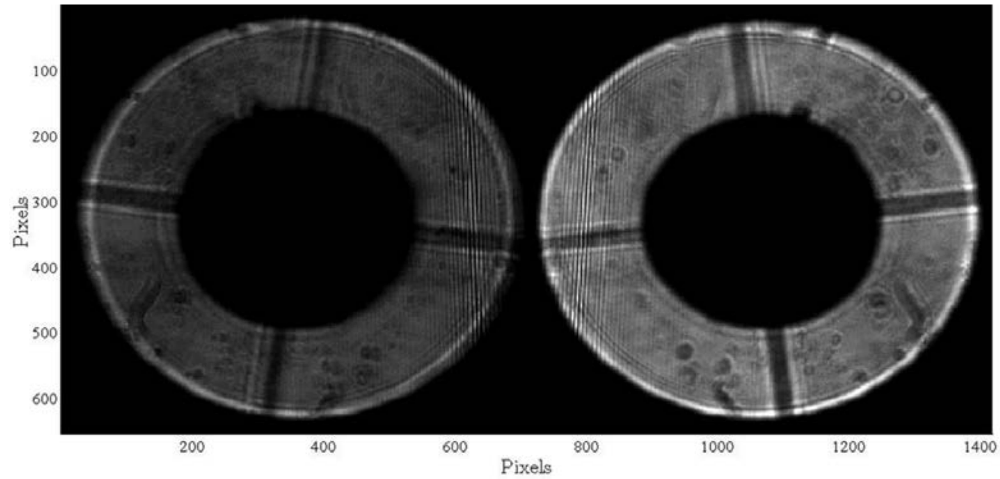

Figure 3. Complementary interferometer channels for the Mira variable S-type star R Andromedae (no spectral filter). The zeroth fringe is set within the aperture, near its edge. Notice that despite the long integration, the fringes are not smeared by the atmospheric turbulence. This is because at zero shear, each point in the aperture interferes with itself, and both beam paths suffer the same atmospheric phase delay. In contrast, most spectrometers are hampered by turbulence, limiting the amount of light through their slit.

We observed a large number of objects, down to m_v=12, in order to see the effect of different colour temperature and narrow lines on the quality of the results. Table 1 lists some of these objects where deeper analysis was performed to see how the narrow lines are detected. The interferograms were recorded during minimal exposure times ranging between few seconds to several hundreds of seconds in order to maintain adequate interference fringes S/N of above 10. These values are following the optimisation of not including in the measured interferogram the DC values (low path difference *d*), and instead concentrating on the higher frequencies, where our lines are better seen (Fig. 1).

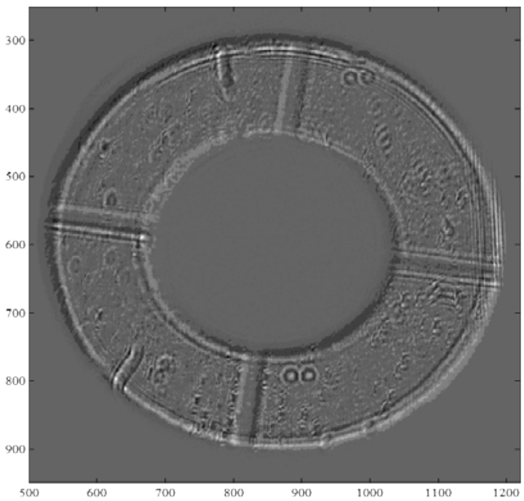

Figure 4. One of the complementary channels (as in Fig. 3), after removal of the constant intensity inside the pupil. Here the zeroth fringe is set outside the aperture, about one telescope radius away. Fringes on the right side of the aperture are now visible thanks to the longer integration time possible when excluding the central fringe.

3. ANALYSIS

The data were processed by their Fourier analysis: the central Fourier lobe (DC) contains no information, and on both its sides there are two conjugate lobes describing the Fourier transform of the spectrum. While the image is two-dimensional, the transform (the spectrum) is along one line, normal to the direction of the fringes. As the delay is given traditionally in cm^{-1} units, after the transform they need to be converted to wave lengths.

Table 1. Astronomical objects observed. The first three stars display Balmer lines, the last three Mg I, Na I and molecular lines.

Star	Spectral Type	m_v	T_{eff} [^oK]
Deneb (α Cygni)	A2Ia	1.25	8525
Procyon A (α Canis Minoris)	F5IV-V	0.34	6530
16 Cygni A	G1.5Vb	5.96	5803
Aldebaran (α Tauri)	K5III	0.86	3910
Betelgeuse (α Orionis)	M2Iab	0.42	3600
R Andromedae	S6/4.5e (Mira variable)	7-15	2000-3500

In the next stage, we compared what happens when we have the zeroth fringe inside the telescope aperture (Fig. 3), and when we push it out of the aperture, measuring only the high-frequency part of the spectrum (Fig. 1). Fig. 5 shows the emergence of narrow spectral lines, and for the four Balmer lines shown, their average depth improves by factors of 19 (Deneb), 9.7 (Procyon A) and 19 (16 Cygni A). Less deep lines in the blue (Ca II) showed lesser improvements of 5.7 (K line) and 2.2 (H line). On Aldebaran, the depth of an Mg I line increased by 13.4 and an Na I line by 4.5.

Lower temperatures allow more complex molecules. For example, it was easy to discern on Betelgeuse TiO, Na I and Fe I lines. As an example we show the spectrum of R Andromedae, with ZrO, Ti and CN lines (on top of atmospheric lines) in Fig. 6. All these narrow lines are not visible from the full interferogram because of its huge background, but clearly seen when using only its wing.

4. SUMMARY

We described here astronomical measurements to verify the notion of using off-centre non-scanned Fourier spectroscopy to measure narrow lines at the presence of strong background signal. A simple analysis of the data provided an order of magnitude improvement in measuring the depth of these narrow lines, simply by not including the central part (zeroth fringe or zero delay) of the spectrum. By using all the detected light for high-frequency measurement, it is possible to see clearly these lines. The effective spectral resolution is thus measured not only by the number of fringes across the aperture (or the interferogram) but also by the starting point in the interferogram. If we can only measure 1000 fringes across the aperture, then our resolution is 10^{-3}. If the central fringe is set ten times further out of the aperture, the resolution will increase to 10^{-4}, and so on.

This signal has to be compared to the noise, here produced by the average level of light in the image. If we know that our lines appear only in a limited part of the spectrum, then a matching spectral band-pass filter will reduce significantly the background light and associated noise. This was also tried successfully, albeit in the visible regime.

This method can be used to measure other astronomical objects, such as active galactic nuclei (AGNs), were distinction is needed between narrow lines and broad lines. For searching for exo-earths, the spectral region to look for complex molecular lines will be in the N band. This is a difficult regime, since the atmosphere, telescope and interferometer all emit at this wave lengths of ~10 µm. This hot contribution adds only to the background, further hiding the lines. The standard solution is to employ fringe modulation[7,8] which is affecting only the signal. Another advantage of modulation is the need for fewer pixels across the spectrum (temporal versus spectral signal), thus allowing smaller detectors. Another problem in the N band is the existence of many terrestrial lines (ozone, water, CO_2) which need to be calibrated away (or the device placed in space).

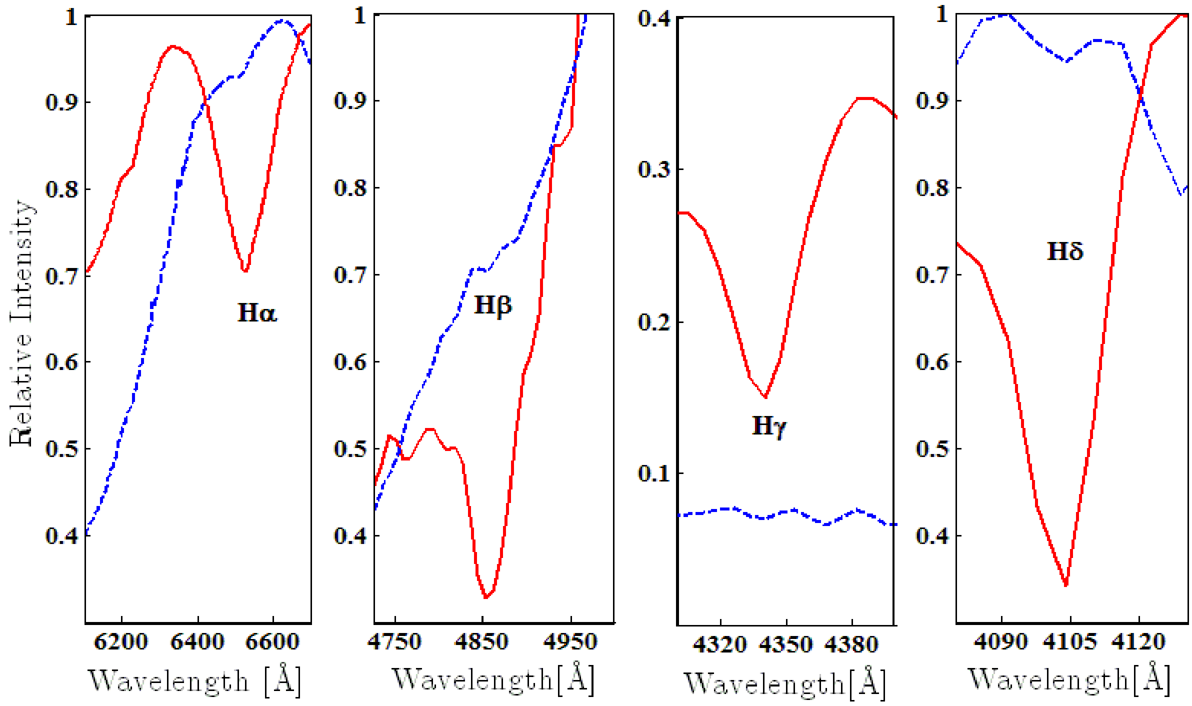

Figure 5. Retrieved spectral Balmer series of Deneb, showing the improvement with non-central Fourier spectrometer. From left to right: Hα, Hβ, Hγ (G band), Hδ lines. The broken lines signify the full spectrum with the zeroth fringe inside the telescope aperture. The full lines display the spectrum when using only the long-delay section of the interferogram.

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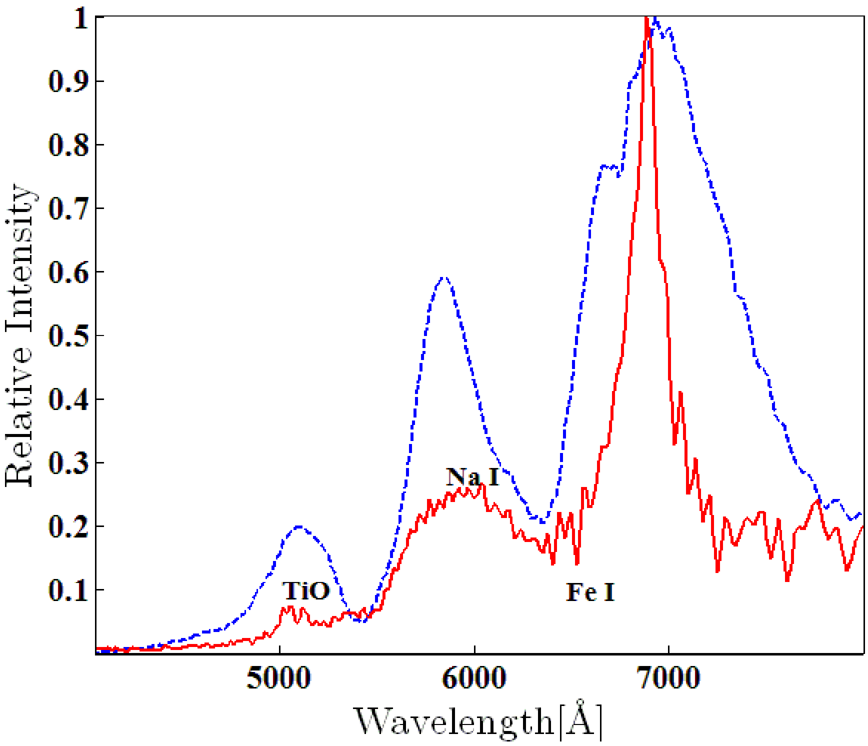

Figure 6. Betelgeuse spectrum (with zero fringe – broken line, at higher frequency – full line). Notice the existence of multiple molecular lines, on top of atmospheric lines in the near IR. These were barely revealed when taking all the interferogram.