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Ultra-high resolution spectroscopy from ground and space for exoplanet atmosphere characterization

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Abstract: Up to date over 4,000 known exoplanets have been detected. High-resolution spectroscopy is becoming crucial to search for biosignatures such as H_2O, CH_4, O_3 and O_2. Detecting and resolving these very narrow absorption lines from low-pressure atmospheric layers requires extreme spectroscopic resolution, also to distinguish telluric and exoplanet signals. Recent studies indicate upcoming Extremely Large Telescopes combined with spectral resolutions of R=300,000-500,000 are ideal to detect O_2 in earth analogs from ground or go to space. To boost typical high-resolution spectrographs (R=100,000) to that level, novel Fabry Perot Interferometer-based concepts have been developed. I will present first on-sky results from our prototype and discuss the future of this technology for exoplanet characterization from ground and space.

Keywords: High resolution spectroscopy; Interferometry; Exoplanet Atmospheres

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1. Introduction

To date, more than 4,000 exoplanets have been discovered from various methods, but only a handful of them are terrestrial planets accessible for future atmospheric characterization [1]. In the next 5-10 years, studying exoplanet atmosphere is a natural step to take. In fact they are being studied now, but mostly of gas giants, often very close to the star due to the current instruments sensitivity. The characterization of biomarkers around terrestrial planet need an ultra-high resolution and precision instrument.

The characterization of the exoplanet atmospheres from ground needs to overcome the signal of Earth's atmosphere. Transmission spectroscopy is an effective method used to unveil the chemical composition and bio-signature gases of an exoplanet atmospheres including their temperature, cloud and haze, as a planet transits its host [2]. Subtle Doppler shifts of the atmospheric spectrum during the transit separate Earth's atmosphere from the exoplanet's signal. However, to successfully quantify atmospheric gases around earth-like exoplanets requires requires extreme spectral resolution (R>100,000)[3]. There are already a number of resolvable atmospheric features such as $H_2O, HCN, CH_4, NH_3, C_2H_2$ detected in HD209458b [4], CO detection ([5]), and TiO([6], [7]). These features are detectable with current instrumental limit of spectral resolution from R=50,000-100,000 on a medium to large (3.5-10 m) telescope.

However, there are interesting features such as molecular oxygen which are beyond current-generation instrumentation. This is because the telluric oxygen signal is too strong. To tackle the problem, novel instrumental concept on the extremely large telescope was presented [8], [9]) using the combination of Fabry Perot based instrument and a traditional high-resolution spectrometer.

Ground-based and space borne observations give complementary information. Low- to high-resolution observations combined provide more accurate and more precise insights from the lower- to the upper-atmosphere [10]. High-resolution ground-based observations provide unique insight into the thermosphere of exoplanets and are sensitive to alkali abundances when properly interpreted and combined with lower resolution observations [11]. The space borne instruments helps avoiding the telluric problem but the current instrumental limit (R=100-1,000) only allows the broadest detection of the spectral feature. Despite, the limited resolving power, the NIR HST instrument allows the detection of, for example, Na, K, H_2O, aerosols. A small number of upcoming missions are dedicated to characterizing exoplanet atmosphere with low-resolution spectrographs, including the Colorado Ultraviolet Transit Experiment (CUTE) [12] and the Atmospheric Remote-Sensing Infrared Exoplanet Large-survey mission (ARIEL), is being executed. The CUTE cubesat project focuses on the near UV regime (0.25 to 0.33 μm) with spectral resolution of 3,000 planned to launch soon. The ARIEL mission, scheduled to launch in 2029, focuses on a larger wavelength range from 0.5-7.8 μm with maximum resolution of R = 100 targeting 1,000 large planets including a few earth-sized ones [13]. Currently in orbit, CHEOPS [14] and TESS [15] will soon provide suitable targets for future instruments suited to the spectroscopic characterisation of exoplanetary atmospheres.

To gain robust insights into exoplanet atmospheres, it is imperative to also develop a high-resolution space-based mission. One of the difficulties is that traditional high-resolution spectrographs (based on echelle or immersion gratings) are bulky and unsuitable for all but the largest, expensive flag-ship space missions (LUVOIR, HabEx). As an alternative, VIPA (Virtually Imaged Phased Array) [16] has promising applications in various astronomical observations in which ultra-high resolution and calibration precision are crucial, such as solar physics research [17], detecting exoplanet with the radial velocity method, and characterizing their atmospheres [18]. VIPA offers structural simplicity, and compact size with reasonable price range. Moreover, with excellent angular dispersion and low polarization sensitivity properties of VIPA, it is suitable to serve as the main dispersion element in ultra-high resolution spectrometer ([19], [20]) for both ground [17] and space instruments [21].

This work demonstrates the efficiency and resolution of VIPA with ground-based observations and discusses its use in space borne mission. Section 2 describes the instrumental setup. The preliminary on-sky result is presented in section 3. We discuss the results and potential space-borne instrumentation projects in section 4.

2. Methods

We demonstrate the capabilities of the VIPA component in a realistic, but simple setting. A solar tracker collects sun light and feeds, through a fiber collimator, a 50 μm fiber. Then the light is fed into the LightMachinery's HyperFine Series spectrometers. It is specifically designed for measuring hyperfine spectra and small spectral shifts. The main disperser in this spectrometer is a VIPA etalon, employed to produce extremely high dispersion in the vertical axis. Next, a diffraction grating is used to disperse overlapping orders in the horizontal direction and to generate a dispersed spectrum of the input light on the CCD as an image. For this particular experiment, we tune the working wavelength of the external spectrometer to the range 760-780 nm. The Krypton lamp is used as a calibration source. The spectrum is obtained as a data file through the LightMachinery's SpectraLok software. This reduction software allows adjusting gain, spectral region of interest, exposure time. It also performs background subtraction, baseline correction and stitching together the successive spectral orders.

3. Results

A preliminary result of the oxygen A band feature is shown in Figure 1. The top panel shows the complex oxygen absorption feature, with several narrow troughs. The bottom panel presents a zoomed view of a narrow wavelength range. The general FWHM is approximately 0.005 nm, which corresponds to the spectral resolution of R=150,000. This was reliably measured from the Krypton calibration line profile in Appendix A.

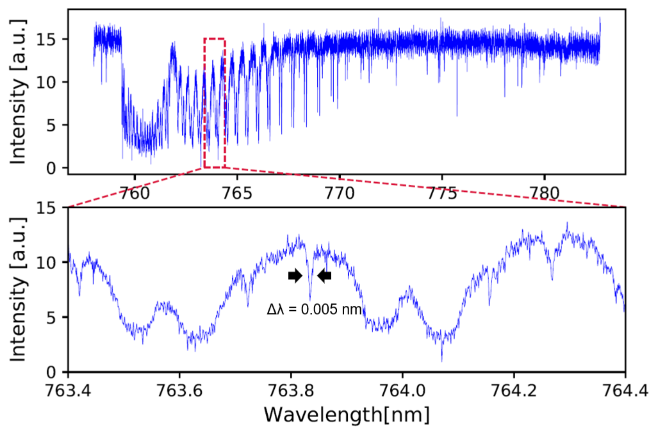

Figure 1. Hyperfine spectral line of telluric oxygen from a VIPA spectrometer. The top panel shows the full high resolution oxygen profile. is a zoom on the doublet signature profile of Oxygen. Arrows highlight the resolving power of approximately 0.005 nm.

4. Discussion & Conclusion

This work demonstrated that VIPA based spectrometer provides and exceeds the high spectral resolution required to characterize exoplanet atmospheres. The high resolution R=150,000 oxygen A-band feature was observed from the solar spectrum with a small collecting area. However, for atmosphere around exoplanets, even with the largest telescopes at high altitudes a high resolution instrument **from ground** produces ambiguous results due to prominent telluric lines.

Therefore, we aim to develop space-based VIPA instrumentation. This way we can overcome the telluric contamination from the earth atmosphere, and enable the characterization of the biomarkers with very dense line profiles such as oxygen and methane. This also implies that the resolution R=150,000 is sufficient. Bourdarot [22] already proposed a 6U cubesat VIPA-based concept for the study of young stars. Here, we propose to develop this space technology to detect exoplanet atmospheric features, including molecular oxygen, but also those in the near infrared (H & K) region such as H_2O and CH_4. This is because multiple bio-signatures and their environmental context are necessary to reliably detect atmospheres hospitable to life. Placing VIPA on a cubesat is also a stepping stone/testbed for a larger interferometry mission to test technological readiness. The telescope aperture on a cubesat will limit to the characterization to large size planets around bright stars (M_v 6-9 mag), such as 55-Cnc and HD-209458 (see [12]). However, demonstrating the technological readiness of VIPA on a cubesat is an important stepping stone towards larger missions. One example of the planned interferometry missions is LIFE [23], and future flag-ship missions on the scale of LUVOIR or HabEx.

Towards a successfully launched mission, several hurdles need to be overcome. Firstly, VIPA is sensitive to small environmental changes (temperature and pressure). Further studies are needed to characterize their behaviour in space environments (e.g., through vacuum chambers) and to justify the stability of the VIPA's interferometer. Additionally, vibrational tests need to be performed.

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Conflicts of Interest: The author declares no conflict of interest. The intention of this proceeding is to demonstrate the performance of VIPA, despite having a small size, and encourage the effort to make the high resolution spectra in space possible.

Appendix

The graphic user interface of the SpectraLok software allows user to execute the data reduction routine, such as background subtraction, wavelength calibration, and read out the observed spectra in real time. It also includes the FWHM analysis of a selected peak. Figure A1 shows one peak of a krypton lamp with $\delta\lambda = 0.0057 nm$ corresponds to spectral resolution of R=133,000.

Figure A1. Peak analysis from the SpectraLok software on the Krypton calibration lamp profile indicate the FWHM of 0.005 nm.

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