EPJ Web of Conferences **47**, 11001 (2013)
DOI: 10.1051/epjconf/20134711001

Characterization of exoplanet atmospheres using high-dispersion spectroscopy with the E-ELT and beyond

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Abstract. Ground-based high-dispersion (R $\sim$ 100,000) spectroscopy provides unique information on exoplanet atmospheres, inaccessible from space - even using the JWST or other future space telescopes. Recent successes in transmission- and dayside spectroscopy using CRIRES on the Very Large Telescope prelude the enormous discovery potential of high-dispersion spectrographs on the E-ELT, such as METIS in the thermal infrared, and HIRES in the optical/near-infrared. This includes the orbital inclination and masses of hundred(s) of non-transiting planets, line-by-line molecular band spectra, planet rotation and global wind patterns, longitudinal spectral variations, and possibly isotopologue ratios. Thinking beyond the E-ELT, we advocate that ultimately a systematic search for oxygen in atmospheres of nearby Earth-like planets can be conducted using large arrays of relatively low-cost flux collector telescopes equipped with high-dispersion spectrographs.

1. INTRODUCTION

Recently, the first successes on exoplanet characterization were obtained using high-dispersion spectroscopy. Spectral signatures from carbon monoxide were detected in the transmission spectrum of HD209458 b [1], and in the dayside spectrum of τ Boötis b[2] [3], all at 2.3 μm using CRIRES on the Very Large Telescope. High-disperion spectroscopic observations such as these provide unique information on exoplanet atmospheres. At R $\sim$ 100,000, molecular bands resolve into tens to hundreds of individual lines of which the signals can be combined through cross-correlation techniques. Since the line-positions are unique, signals from molecular gases can be uniquely identified. In contrast, low-resolution spectroscopy and spectrophotometric observations, in particular with a limited number of data points, often produce ambiguous results, since molecular bands can overlap and can strongly vary in prominence depending on the temperature structure of the planet atmosphere [4].

At a spectral resolution of a few km/sec, these measurements become highly sensitive to Doppler shifts from the planet orbital motion, which for hot Jupiters can be up to > 150 km/sec. It means that the planet lines can move by many km/sec over the course of an observing night. This is an important aspect of the observational technique, because it allows the features generated in the exoplanet atmosphere to be separated from the stationary telluric and quasi-stationary stellar lines, which strongly dominate the spectrum.

The sensitivity of high-dispersion spectroscopy to the radial velocity variations of an exoplanet means that the radial component of the orbital velocity of the planet can be measured. In the case of transiting systems, for which the system inclinations are known accurately, the combination of the velocities of the planet and host star solves for the masses of the two objects - in the same way as has been done for double-line eclipsing binaries for one hundred years. When performed at high enough

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precision, this will result a stellar mass determination at a precision of $\sim$1%, constraining the age of the system. In the case of non-transiting planets, determination of the radial component of the orbital velocity of the planet leads to the system inclination, and therefore the true mass of the planet [2]. In this case the stellar mass as estimated from spectroscopy, and the orbital period of the planet, give the orbital distance and the orbital velocity of the planet. The radial component of the latter subsequently leads to the orbital inclination.

2. HIGH-DISPERSION SPECTROSCOPY WITH THE E-ELT

Europe's next-generation ground-based telescope for optical and infrared wavelengths, the 39 m E-ELT, has two high dispersion spectrographs in its instrumentation roadmap. Instrument nr. 3, the Mid-infrared E-ELT Imager and Spectrograph METIS [5], will have an $R = 100,000$ spectrograph covering $\lambda = 2.9$–$5.0\,\mu$m. In addition, HIRES, instrument nr. 4 or 5, will be an optical to near-infrared spectrograph with an $R = 100,000$ mode [6]. Compared to current observations with CRIRES on the VLT, E-ELT spectroscopy of bright stars, for which sky background does not significantly contribute to the noise budget, will be about a factor 25 more efficient for a fixed wavelength range (excluding possible differences in slit losses). The envisaged cross-dispersed mode for HIRES adds another order of magnitude to this due to the significantly larger instantaneous wavelength range. This implies that the recent successes with CRIRES on exoplanet characterization prelude an enormous discovery potential for the E-ELT.

The high-precision stellar and planetary mass determinations for transiting systems and measurements of the orbital inclination and mass of non-transiting planets that can be done with the VLT for a handful of planets, will become possible for hundreds of systems. A whole range of molecular gases will be detectable, from possible metal-oxides in the optical, to water, methane, carbon dioxide and ammonia in the near- and thermal infrared. In addition, optical observations will be sensitive to reflected starlight, determining the albedo of a planet and constraining its heat budget.

The strong increase in signal-to-noise of observations with HIRES and METIS at the E-ELT compared to those currently performed means that a whole new range of measurements are possible:

- **Line by line planet spectrum.** Instead of an ensemble signal from the combination of many individual lines, a real high-resolution planet spectrum can be constructed, revealing the strengths of individual lines in a molecular band. The lines are produced at a range of different atmospheric altitudes and pressures, meaning that they probe the planet atmospheric temperature-pressure profile in a unique way, with only the molecular abundance as a free parameter. For example, the presence of a thermal inversion layer at a certain altitude range within the planet's photosphere would show up unambiguously as a set of molecular emission lines.
- **Planet rotation and global wind patterns.** A crucial parameter in atmospheric physics is the global circulation on a planet, in particular in cases where the dayside hemisphere is strongly irradiated by the star, as for hot Jupiters. It governs the level at which stellar energy that is absorbed on the planet dayside-hemisphere is transported to the night-side. High-resolution spectroscopy can provide important information on global wind patterns, as shown by the tentative detection of a $\sim$2 km/sec wind blowing from the hot dayside to the cool nightside on HD209458b [1]. E-ELT observations will be able to reveal detailed signatures of planet rotation and circulation, which show up as line broadening, and velocity-shifts during ingress and egress of a transit when only part of the planet atmosphere is illuminated by the star. This will show to what extent close-in planets are tidally locked or not.
- **Longitudinal spectral variations.** Another aspect of high-resolution dayside spectroscopy is that a planet signal can be retrieved along a large part of its orbit, not necessarily directly around secondary eclipse (see e.g. the CRIRES observations of tau Bootis [2]). This means that molecular signals can be

obtained as function of planet longitude, c.f. from the morning-side to the evening-side of the planet, revealing possible photochemical processes or variations in the atmospheric temperature structure.

- **Isotopologue ratios.** HIRES observations of the brightest systems may reveal molecular isotopologue ratios, providing insights in the atmospheric evolution of exoplanets, e.g. through evaporation.

3. BIOMARKERS AND THE POTENTIAL OF LOW-COST FLUX COLLECTOR TELESCOPES

High-dispersion spectroscopy with the E-ELT will push the frontier of exoplanet atmospheric characterization from hot Jupiters to cooler and smaller planets. The ultimate goal of extrasolar planet research is arguably the detection of biomarker gases that may provide evidence for the existence of extraterrestrial life [7].

We recently investigated to what extend biomarker gases in Earth-like atmospheres could be probed with high-dispersion spectroscopy using future ground-based telescopes [8]. The 9.6 μm ozone feature is practically inaccessible from the ground due to the high thermal background. However, the oxygen A-band at 7600 Åis very suitable for high-dispersion spectroscopy, also because it consists of ~50 strong lines with near-100% transmission in between. In the Earth atmosphere, molecular oxygen has a constant volume mixing ratio up to the top of the mesosphere at 85 km altitude. Simulations of the transmission spectrum of an Earth-twin at R = 100, 000 result in a signal of 5×10^{-5} for the strongest oxygen lines with respect to the continuum flux from an M5V dwarf star [8]. This is only a factor 3 smaller than the carbon monoxide signal detected in the dayside spectrum of τ Boötis [2]. Transit geometry predicts that if all M5V dwarf stars would have Earth-like planets in their habitable zones ($\eta_E = 1$), the brightest transiting systems would be expected in the I = 10.0–11.8 magnitude range (V-I ~ 3.6). We simulated high-dispersion E-ELT observations of such systems that show one would require 10 to 50 transits for a 5 σ oxygen detection of a twin-Earth planet, which can be obtained from one location on Earth within a time scale of 4 to 20 years. It means that only if Earth-like planets in the habitable zones of late M-dwarfs are very common, and if particularly bright systems exists, we can hope to successfully detect oxygen in twin-Earth atmospheres with the E-ELT. Note that oxygen transmission spectroscopy of twin-Earth planets around earlier type stars such as our Sun are out of the question. Although the SNR achieved per transit will be similar to that for planets around late M-dwarfs (the lower contrast is compensated by the brighter stars and longer transit durations), the long orbital periods of planets in the habitable zones of sunlike stars mean that it will take 80 to 400 years with the E-ELT to obtain sufficient SNR for a secure detection, even if twin-Earths are very common [8].

However, in many ways the next generation E-ELTs will be overdesigned for high-dispersion spectroscopy of bright stars. While they will be built to provide high sensitivity at the highest possible angular resolution over a significant field of view, the observations described above require a large collecting area, but can easily deal with poor image quality and a small field size. In particular in the optical, the sky background sets a requirement on the PSF size of ~5 arcseconds. This is in the realm of flux collector telescopes, and we see no great engineering challenges in building collecting areas significantly larger than that of the ELT for a fraction of the cost [8]. Since the size of an Echelle spectrograph scales with the size of the primary mirror and the angular size of the entrance slit, significant developments in spectrometer design are required to reduce their size - e.g. through extreme image slicing techniques (note that only one Echelle order is required). Ultimately, a collecting area of a few football fields equipped with high-dispersion spectrographs will be required to perform a statistical study of life-bearing planets in the solar neighborhood.

I thank Rudolf le Poole, Remco de Kok, Matteo Brogi, and Jayne Birkby for the many discussions on this subject.

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