High-dispersion spectroscopy of extrasolar planets: from CO in hot Jupiters to O₂ in exo-Earths

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Ground-based high-dispersion spectroscopy could reveal molecular oxygen as a biomarker gas in the atmospheres of twin-Earths transiting red dwarf stars within the next 25 years. The required contrasts are only a factor of 3 lower than that already achieved for carbon monoxide in hot Jupiter atmospheres today but will need much larger telescopes because the target stars will be orders of magnitude fainter. If extraterrestrial life is very common and can therefore be found on planets around the most nearby red dwarf stars, it may be detectable via transmission spectroscopy with the next-generation extremely large telescopes. However, it is likely that significantly more collecting area is required for this. This can be achieved through the development of low-cost flux collector technology, which combines a large collecting area with a low but sufficient image quality for high-dispersion spectroscopy of bright stars.

1. The extrasolar planet revolution

With the more than 800 planets found to date [1], it is hard to imagine that only 20 years ago the first exoplanet around a main-sequence star had still to be discovered. The first detections of hot Jupiters [2,3] then showed the immense potential of the radial velocity (RV) technique, which marked the onset of the RV monitoring of hundreds of stars in the solar neighbourhood and of the development of dedicated, extremely stable spectrographs. This has cumulated in the current estimates of the distribution of exoplanets as the function of mass and stellar type, and their orbital distribution [4,5]. These indicate that Earth-mass planets are likely to be very abundant in the Milky Way, which has been confirmed by
Figure 1. The atmospheres of transiting exoplanets can be studied in three ways, during transit when starlight filters through the atmosphere, using the eclipse when all planet radiation is temporarily obscured from view and by measuring the variation in the day/nightside contribution as function of orbital phase. (Online version in colour.)

the recent discovery of an Earth-mass planet closely orbiting our neighbour star Alpha Centauri B [6]. It is only a matter of time before the first twin-Earth planet, in the habitable zone of its parent star, will be found.

Although the RV technique has been (and still is) seminal for the exploration of the planet population in our galaxy, it does not reveal much about the planets themselves, except for their main orbital parameters and lower limits on their masses. Only when their light is detected directly will it be possible to constrain the sizes and mean densities of these planets, and possibly reveal atmospheric features. However, direct imaging is extremely challenging owing to the huge contrasts with respect to their bright host stars. Recent successes, such as the discovery of a multiple planet system around HR 8799 [7] and the planet-like object around Fomalhaut [8], are limited to very young systems for which the star/planet contrasts are reduced by several orders of magnitude, because the planets are still hot from their formation process and strongly radiate in the infrared. A new generation of extreme coronagraphs, such as SPHERE on the Very Large Telescope (VLT) [9] and GPI on the Gemini telescope [10], are becoming operational; they are expected to push the contrast limits considerably further, but may still stop short of detecting mature exoplanet systems. The latter are expected to be within the range for the future extremely large telescopes (ELTs) [11].

(a) Transiting extrasolar planets

A suite of already very successful techniques to characterize mature exoplanets makes use of the small fraction of planets that transit the disc of their host stars. The amount of light blocked by the planet reveals the planet size and combined with RV measurements leads to the mean density, constraining the bulk composition of the planet [12]. In addition, the planet atmosphere can be studied in several ways [13]. During transit, starlight filters through the atmosphere and leaves an absorption signature of the atmospheric constituencies (figure 1). Half an orbit later, the planet is blocked by the star, called the secondary eclipse. By comparing the radiation from the system during the eclipse with that just before and after, the thermal emission from the planet’s dayside, possibly modulated by molecular bands, and/or reflected light can be measured. A handful of atomic and molecular gases have been identified, such as water, methane and carbon monoxide [14–16]. In addition, by monitoring the flux from a system along the planetary orbit, the changing phases can be measured. Varying contributions from a planet’s day- and nightside hemispheres cause a minute change in the total flux from the system, allowing the temperature distribution on the planet to be mapped [17–19].

2. The ultimate goal: finding extraterrestrial life

Arguably, the ultimate goal of extrasolar planet research is, one day, to detect extraterrestrial life. Any form of life interacting with its planet atmosphere will drive that atmosphere to a state of chemical disequilibrium. Detection of such disequilibrium will serve as evidence of biological
activity if its strength makes it impossible to be produced by non-biological processes [20,21]. For example, on the Earth oxygen and hydrocarbons coexist in the atmosphere, which is incompatible on a long-term basis considering abiotic processes alone [22]. Originally, the concept of probing biomarker gases was developed in the context of Mars experiments. Subsequently, when the first exoplanets were being discovered, this idea was expanded to planets orbiting stars other than the Sun [23–25].

(a) Direct imaging techniques: the Darwin and Terrestrial Planet Finder space missions

Over the last two decades, an enormous effort has been put into the detailed design of a space mission that could detect biomarkers in nearby planetary systems. The contrast between the light from an Earth-twin and that of a Sun-like star is huge, up to 10 orders of magnitude at optical wavelengths. The most important aspect of an instrument that searches and characterizes exoplanets is therefore its capability to separate the starlight from that of the planet. As the contrast in the mid-infrared is approximately three orders of magnitude more favourable owing to the thermal radiation of the planet, the ozone 9.6 μm absorption band is the biomarker of choice for space-based coronographic or interferometric techniques [26,27].

The initial idea for the Darwin mission [28,29] was proposed in 1993. It was to be composed of four or five free-flying spacecraft carrying out high-resolution imaging using nulling interferometry. After undergoing a design study, the European Space Agency stopped all further developments in 2007. On a similar time scale, the Terrestrial Planet Finder [30,31] mission was proposed to NASA, including two designs, a nulling interferometer and a visible light coronograph. This project has also subsequently been cancelled. Owing to the long lead times for such ambitious projects, it is very unlikely that a similar type of mission will be designed, built and launched within the next 25 years. Developments of direct imaging techniques have certainly not come to a halt. Great advances are being made using ground-based instrumentation and new data analysis techniques. However, the contrasts that are achieved are still several orders of magnitude away from those needed to characterize the atmospheres of Earth-like planets. Moreover, as for any ground-based observations, the most favourable absorption bands in the mid-infrared are not accessible owing to the high sky background and the strong absorption in the Earth’s atmosphere.

(b) Detecting biomarkers in transiting planet systems

Atmospheric characterization of hot Jupiters has been shown to be well in the range of current-day instrumentation, from both space and the ground. As transit probabilities range from 10% for hot Jupiters to 0.5% for temperate planets orbiting solar-type stars, the nearest transiting systems are typically two to six times further away (and 2.5–6 magnitudes fainter) than their non-transiting counterparts. Importantly, these techniques are significantly more sensitive for planets transiting cool dwarf stars. This has so far culminated in the atmospheric characterization of a planet twice the size of the Earth, transiting the M5 red dwarf star GJ1214 [32–35].

The James Webb Space Telescope (JWST), to be launched in 2018, will be an order of magnitude more sensitive than the Hubble Space Telescope, pushing planet characterization down to significantly cooler and smaller planets than today. However, it is uncertain whether the JWST will be sensitive and stable enough to search for biomarkers in temperate rocky planets, even around cool red dwarf stars [36–39].

3. Ground-based high-dispersion spectroscopy

Recently, ground-based high-dispersion spectroscopy has really taken off as a way to characterize extrasolar planet atmospheres. Already in the late 1990s, the first observations to detect reflected light using high-resolution spectroscopy were attempted. However, the optical albedos of
hot Jupiters turned out to be very low [40,41]. In addition, attempts to detect molecular features in the thermal emission spectrum [42] and transmission signal [43] only resulted in upper limits.

In 2010, observations with the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES) on the VLT of the European Southern Observatory have resulted in the first detection of an exoplanet atmosphere using high-dispersion spectroscopy. Snellen et al. [44] observed the hot Jupiter HD209458b during transit, targeting the 2.3 µm band of carbon monoxide. At a spectral dispersion of \( R = 100,000 \), the carbon monoxide band resolves into tens of individual lines, which shift in wavelength owing to a change in the radial component of the orbital motion of the planet during the transit (figure 2). This not only results in a direct measurement of the orbital velocity of the planet, it also allows the (quasi-)stationary telluric and stellar lines to be filtered out during the data analysis process, without the need for calibration stars to characterize the Earth’s atmosphere and instrument. The planet orbital velocity, determined to be 140 ± 10 km s\(^{-1}\), in combination with the stellar RV variations led to model-independent mass determinations of the planet and star, in the same way as has been done for double-line eclipsing binaries for many decades.

While high-dispersion transit observations target absorption in the starlight that filters through a planet’s atmosphere, the thermal emission of a planet can be observed at any orbital phase. Depending on the temperature–pressure profile of the planet’s atmosphere, molecular lines produced in the upper layers of the photosphere will appear as absorption or emission according to whether the temperature is decreasing or increasing (cf. the case of a thermal inversion) as a function of altitude. These observations of thermal emission do not require the planet to transit—non-transiting planets are actually preferred because they are more common and therefore found around brighter host stars. In that case, detection reveals the radial component of the orbital velocity of the planet, which in combination with the orbital period and stellar mass points to the orbital inclination of the system. Brogi et al. [45] observed the non-transiting planet \( \tau \) Boötis, again targeting carbon monoxide at 2.3 µm, for 3 × 5 h using CRIRES on the VLT. The observations show a clear detection at approximately 6σ showing carbon monoxide in absorption and pointing to an orbital inclination of 44.5 ± 1.5°. The line broadening in the spectrum of the host star is such that if it rotates at the same angle, its rotation period is similar to the orbital period of the planet. This suggests that the star is tidally locked (see also [46]).

Also the hot Jupiter 51 Pegasi b was targeted with CRIRES with the same set-up but with a somewhat more ambiguous outcome [47]. The observations appear to show a clear detection from water and carbon monoxide, but only in the first two nights of the data. The third night shows no signal, meaning that either an (unexplained) instrumental signal played a role or a strong weather pattern changed the global appearance of the planet over the course of a few days.
4. High-dispersion spectroscopy in the era of extremely large telescopes

The availability of extremely large telescopes with high-dispersion spectral capabilities will revolutionize the characterization of extrasolar planets. Concentrating on the European Extremely Large Telescope (E-ELT), two planned instruments have a \( R = 100,000 \) spectrograph in their design: METIS performing at more than 3\( \mu \)m [11] and HIRES (http://www.ast.cam.ac.uk/ioa/meetings/elthires) at optical to near-infrared wavelengths. Assuming similar slit-losses for the E-ELT spectrographs as for CRIRES, they will collect approximately 25 times more photons per wavelength step. Given that the instantaneous wavelength range is envisaged to be a factor of a few larger, the E-ELT will be a factor of 50–100 times more powerful than the VLT used currently for this type of observations.

The E-ELT becoming available in the year 2024 \( \pm \) 3, the JWST is likely to have been operational for some time. High-dispersion E-ELT spectroscopy will probe unique aspects of exoplanet atmospheres, not accessible with the JWST. With a signal-to-noise ratio increase of up to an order of magnitude compared with the VLT, planet rotation and circulation can be measured—a crucial ingredient for understanding planet atmospheres. When the planet transits the star, the atmosphere is seen as an annulus around the planet limb, and the rotation of the planet results in the atmosphere on one side being redshifted and that on the other side being blueshifted, altering the line profile of the absorption lines which can be measured, and thus the planet rotation determined (see [48] for theoretical simulations). Note that this is only expected to be observable for large and hot planets.

The high signal-to-noise ratio achieved with the E-ELT means that for the brightest systems the molecular absorption signals can be determined as a function of orbital phase. This means that it will be possible to derive variations in molecular abundance ratios and/or in the temperature-pressure profile as a function of planet longitude (from the morning, midday, evening, into the nightside), e.g. those caused by photochemical processes. Also, instead of combining the signal from one molecule using all its available lines by cross-correlation, with the E-ELT the signal-to-noise ratio will be high enough to determine the line strengths of the individual lines in a molecular band. Individual lines will be formed at different altitudes, probing the temperature-pressure profile of the planet’s atmosphere in a unique way. With the instrumentation on the E-ELT, it may even be possible to detect different molecular isotopologues and determine isotope ratios, giving insights into the evolutionary history of the atmospheres. All these scientific endeavours cannot be performed with the JWST.

The large collecting area of the E-ELT will enable the detection of molecular features in significantly smaller and/or cooler planets than hot Jupiters, and it is in this regime where there will be an important synergy with the JWST. Some of the central parts of spectroscopically active molecules at low temperatures, such as water and methane, will not be accessible from the ground. Only with space observations will it be possible to obtain an overall view of exoplanet spectra from the red-optical to mid-infrared. However, in particular when observing small, cool planets at or near its detection limit, the JWST will only be able to detect features at very low spectral resolution, meaning that it will be very challenging to identify and quantify molecular features because they overlap and are strongly dependent on the temperature distribution in the planet’s atmosphere. For these objects, high-dispersion observations of the E-ELT at a specific wavelength at significantly higher signal-to-noise ratio will be needed to unambiguously identify molecular gases.

5. Detection of biomarker oxygen with high-dispersion spectroscopy

We recently looked into the question of whether biomarker gases can be detected in Earth-like planet atmospheres with the E-ELT [49]. While from space it is generally thought that the ozone 9.6\( \mu \)m feature is the best to target, it is practically inaccessible from the ground owing to the high thermal background at this wavelength. Fortunately, the oxygen A-band at 7600 Å is very suitable for high-dispersion spectroscopy, consisting of approximately 50 strong lines with almost
complete transparency in between [49]. This means that a Doppler-shifted extraterrestrial oxygen signal can potentially be observed in between the telluric lines. At a resolution of $R = 100\,000$, the oxygen absorption causes the effective radius of the Earth to increase by approximately 80 km in the centre of the absorption lines during transit [49].

Assuming an M5V host star, this results in a contrast of $5 \times 10^{-5}$ for the strongest lines. This is only a factor of approximately 3 smaller than the carbon monoxide signal detected in the thermal dayside emission spectrum of the hot Jupiter τ Boötis b [45]. However, the potential M5V host stars will be many magnitudes fainter than τ Boötis, meaning that a much larger collecting area is required than that provided by the 8 m VLT. Using the observed local M-dwarf number counts and the transit probability for a planet in their habitable zones (implying an orbital period approx. 12 days), the brightest transiting systems are found to be expected at an I-band magnitude of $I = 10 - 11.8 (V - I = 3.6)$, assuming that all stars have a twin-Earth planet in their habitable zone ($\eta_e = 1$).

Subsequently, high-dispersion E-ELT observations were simulated showing that it would require a few dozen transit observations to reach a 5σ detection. As only a fraction of the occult transits can be observed from one particular observatory on the Earth, it will take 4–20 years to achieve this (using a few observing nights per year). As $\eta_e$ is likely to be significantly smaller than unity [50], it may be a bridge too far to detect oxygen as a biomarker in a twin-Earth atmosphere, but the fact that it appears to be close to the realm of possibilities shows the enormous discovery potential of high-dispersion spectroscopy with future ELT telescopes. Note that, although the signal-to-noise ratio per transit of oxygen in twin-Earth atmospheres around the brightest expected solar-type stars is similar to those around M-dwarfs, their transits are so infrequently observed that it will take 80–400 years to reach a 5σ detection [49].

6. Flux collector telescopes

We advocate that there is a way to surpass the performance of the next-generation ELTs, without the need for an unrealistically costly telescope system. For high-dispersion spectroscopy of bright stars, the ELTs are in some way overdesigned, because they will be built to provide the highest possible angular resolution over a significant field of view—driving many of the design specifications.

High-dispersion spectroscopy of bright stars can easily deal with a significantly lower image quality, particularly in the optical, with background contamination setting a requirement of a approximately 5 arcsecond point spread function (PSF), depending on the target magnitude. In addition, there is no requirement on the field size—only the target star itself will need to be observed. These specifications are in the realm of flux collectors, e.g. used as solar energy collectors, Cherenkov telescopes [51] or sub-millimetre dishes [52] (if necessary with an optically...
reflective surface). Do note, however, that, for a conventional echelle spectrograph, the size of the grating is proportional to both the size of the primary mirror of the telescope and the angular size of the entrance slit. This would make such a spectrograph very large for the upcoming ELTs, and even significantly larger for a flux collector telescope, because by definition the PSF for a star and therefore the required size of the entrance slit is order(s) of magnitude larger. This can be mitigated, for example, by using extreme image slicing techniques, in which the PSF is divided into a number of separate slices, or probed by a bundle of fibres, which are subsequently aligned along a then much narrower slit. There is room for extreme image slicing techniques because only one echelle order is, in principle, required to sample the whole O2 band. The challenge will be to build such a telescope system with the huge collecting area required, e.g. at least a few times the area of the E-ELT, to perform a statistical survey of extraterrestrial life in the solar neighbourhood. However, this does not need to be done in one go. Already a fully dedicated 5 m flux collector with the specifications above will be highly competitive with the current 8–10 m class telescopes, which would be an ideal testbed for the use of flux collectors for high-dispersion spectroscopy. In the same way a 15 m size flux collector will be competitive in the ELT era, which could serve as a stepping stone for a large array of such telescope systems (figure 3) to detect extraterrestrial life.

Acknowledgements. I am much in debt to my collaborators, Matteo Brogi, Remco de Kok, Rudolf le Poole, Jayne Birkby, Ernst de Mooij, Simon Albrecht and Christoph Keller.

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