

Atmospheres of hot alien Worlds Brogi, M.

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Cover Page



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7

Future exoplanet characterization at high spectral resolution

This thesis has mostly focused on the use of ground-based, high-resolution spectroscopy to characterize the atmospheres of exoplanets. This Chapter is devoted to summarize the unique advantages of this novel technique, the current achievements, possible improvements during the next 5-10 years, and the prospects for the next generation of Extremely Large Telescopes (ELTs).

7.1 Advantages of high-resolution spectroscopy

High-resolution spectroscopy is a particularly robust technique for constraining some of the basic properties of exoplanet atmospheres. It is much less affected by systematics than low-resolution or photometric observations, with noise levels only 10-20% away from the photon noise in most of the cases (see, e.g., Chapter 4). The following planet properties are particularly well constrained by this observational technique:

- Atmospheric composition: due to the fact that at very high spectral resolution each molecular species has a unique fingerprint, it is possible to robustly determine the composition of exoplanet atmospheres with this method. This means that, for instance, no spurious signal can be obtained by cross-correlating water lines with methane or carbon monoxide lines. It is a big advantage over low-resolution spectroscopy or broad-band photometry, for which molecular bands often overlap, introducing a level of ambiguity in the interpretation;
- **Planet radial velocities:** high-resolution spectroscopy probes the variations in the planet radial velocity while it moves across the orbit. By pairing planet and stellar radial velocities, the system is treated as a spectroscopic binary and the planet/star mass ratio is determined. For non-transiting planets with a good estimate of the host-star mass, we can solve for the true planet mass and the orbital inclination. In the case of evolved, close-in planet, this is so far the only method capable to access the atmospheres of bodies which do not transit. In this thesis we have determined the planet mass and orbital inclination of non-transiting planets in Chapters 2, 3, and 4;
- **Bulk thermal atmospheric structure:** dayside high-dispersion observations are particularly sensitive to the thermal structure of the planet atmosphere, e.g., to the presence or the absence of a thermal inversion layer. They measure

the depth of molecular lines relative to each other and relative to the planet continuum, which is proportional to the temperature difference between the planet photosphere (formed deep in the atmosphere) and the core of the lines (formed higher up in the atmosphere). For temperature decreasing with pressure (non-inverted atmosphere), the core of the line will form in an atmospheric layer cooler than the continuum, resulting in *absorption* lines. For temperature increasing with altitude (thermal inversion), the core of the line will form in a hotter layer and *emission* lines will be observed. It is worth noting that all the dayside observations presented in this thesis (Chapters 2, 3, and 4) find atmospheres lacking strong thermal inversions. This confirms the general trend of most of the exoplanets characterized to date.

• **Relative molecular abundances and C/O ratio:** high-dispersion observations cannot effectively constrain *absolute* molecular abundances (see below). However, they can provide a measurement of *relative* molecular abundances. These can be translated into a measurement of the atmospheric C/O ratio for hot Jupiters. Current attempts to perform this type of analysis (see Chapters 4 and 6) are limited by the incomplete sensitivity to all the major carbon- and oxygen-bearing molecules in a small spectral range, but see Section 7.3 for strategies to overcome this limitation.

7.2 Current limits of high-resolution spectroscopy

High-dispersion observations have only recently became successful in characterizing exoplanets, and mostly due to the work presented in this thesis. It is therefore important to highlight not only the advantages, but also the challenges potentially affecting the method, in order to stimulate a constructive participation of a broader community. In this Section the main limits of the technique, together with possible solutions, are presented.

- No absolute abundances: as explained in Section 7.1, observations at high spectral resolution are sensitive to the temperature difference between the two atmospheric layers at which the planet continuum (deep in the atmosphere) and the line cores (higher up in the atmosphere) are formed. This temperature contrast is degenerate with the atmospheric lapse rate (i.e., the rate at which temperature changes with pressure) and the molecular abundances, meaning that multiple combinations of the two variables produce the same observed line depth. Furthermore, our data analysis removes any information about absolute fluxes and broad-band spectral variations. Therefore, there is an additional degree of freedom regarding the temperature of the planet continuum. This renders high-dispersion observations in a narrow spectral range particularly insensitive to absolute molecular abundances and the detailed temperature-pressure (T/p) profile;
- The observable sample is small: high-resolution spectroscopy is currently limited to stars brighter than K = 7-8 mag and planets with orbital periods less

than 7-8 days, for 10 hours of integration time with a CRIRES-like spectrograph at a 8-meter telescope. This translates in a sample of \sim 10 exoplanet systems across the entire sky;

- Lack of NIR high-resolution spectrographs: in July 2014, CRIRES will be removed from the VLT for an upgrade, and it will probably stay idle for 3-4 years. If that will happen, there will be no NIR spectrograph with resolution ≥ 50,000 and mounted to a 8-10m class telescope in the world.
- Molecular line lists at high temperatures: exoplanet characterization at high spectral resolution is possibly limited by the lack of accurate line lists for the temperatures relevant to close-in planets (T > 1000 K). Incompleteness or inaccuracies in the line position and strength could potentially smear the cross-correlation signal or even cancel it completely (Hoeijmakers et al. in prep.). In response to the need of the exoplanet community for accurate laboratory measurements and quantum-mechanical simulations, updated catalogues have been recently published for a good fraction of molecules relevant to the extreme conditions of hot planets (e.g. Barber et al. 2014; Yurchenko & Tennyson 2014).

7.3 The coming years

During the past 3-4 years, exoplanet characterization at very high spectral resolution has just started to show its full potential. Before the next-generation of Extremely Large Telescopes will go online, it is possible to improve and extend the achievements of this novel observational method in the following ways:

- Observing a wider spectral range: relative molecular abundances can be better constrained by observing across a wider spectral range, or at multiple wavelengths. As de Kok et al. (2014) pointed out for a CRIRES-like instrument, the best regions to detect the main C- and O-bearing molecules are around 2.3 μ m and 3.5 μ m. These bands contain significant opacity from CO, CO₂, H₂O and CH₄. It is also possible to test for disequilibrium chemistry, for example by targeting HCN and C₂H₂ at 3.1 μ m. These two molecular species are also important when testing carbon-rich (C/O > 1) atmospheres, as their abundances in chemical equilibrium become comparable to that of CH₄ (Madhusudhan 2012);
- Improved design of NIR spectrographs: the lack of high-resolution infrared spectrographs mounted at 8-10m class telescopes can largely be compensated by instruments with slightly lower resolution mounted at 3-4m class telescopes and having significantly wider spectral range and/or a better throughput. The cross-correlation signal increases approximately with the square root of the number of deep molecular lines, which corresponds to the square root of the spectral range. Furthermore, by substituting narrow entrance slits with, e.g., image slicers and scrambled fibers, the instrument throughput could easily

increase to $\sim 15\%$, a factor of ~ 5 greater than for CRIRES. This means that, in terms of signal-to-noise, an instrument capable to cover one entire near-infrared band with the above throughput should be a factor of 5-6 faster than CRIRES in detecting exoplanet atmospheres, which means it would still be advantaged even if mounted at a 2-meter telescope.

The high-resolution signal is also strongly dependent on spectral resolution. Since for giant planets the observed spectral lines are unresolved, their FWHM scales approximately linearly with the resolution, which implies the contrast between the continuum and the line core also scales linearly with the spectral resolution¹ This means that a spectrograph such as NIRSPEC at Keck with R = 25,000 should deliver approximately 1/2 of the signal of CRIRES for equal observing time and spectral range.

- **Pairing low- and high-resolution observations:** some of the degeneracies in the atmospheric retrieval can be solved by pairing observations at high and low spectral resolution. In particular, the planet continuum temperature could be estimated for transiting planets from secondary-eclipse measurements, and for non-transiting planet it could be constrained from broad-band phase-curve variations.
- Developing consistent retrieval algorithms: the amount of complementary information carried by low- and high-resolution spectroscopy extends beyond the point discussed above. The two spectral resolution regimes probe different atmospheric pressures, in both transmission and dayside spectroscopy. In order to extract the maximum information from the observations, we need self-consistent retrieval algorithms capable to take all aspects into account. In particular, Bayesian retrieval seems to be favored in this sense, given the high number of (possibly correlated) parameters to include;
- Optical high-resolution spectroscopy: early attempts to detect reflected light from exoplanets (Collier Cameron et al. 1999; Charbonneau et al. 1999) only resulted in upper limits, because most of the hot Jupiters have a very low Bond albedo, and because instruments were limited in resolution, spectral range, and stability. Since a few exoplanet hint today towards a relatively high Bond albedo (e.g., Kepler-7 b, Demory et al. 2011), in the near future it might be possible to detect reflected light at high resolution. Furthermore, the planets suspected to host an atmospheric inversion layer should have high-altitude absorbers such as TiO or VO (Hubeny et al. 2003), capable to block the incoming visible starlight. These species should show detectable molecular lines in the optical transmission spectra of the most irradiated exoplanets.
- Detecting atmospheric circulation: hot-Jupiter atmospheres are thought to show two main regimes of atmospheric circulation, namely a strong day- to night-side flow or an equatorial super-rotation due to eastward jets (Miller-Ricci Kempton & Rauscher 2012; Showman et al. 2013). Interestingly, these two

¹This scaling approximately holds for R = 20,000-200,000. At lower resolutions, blending of molecular lines becomes dominant. At higher resolutions, the lines start to be resolved.

regimes would produce a detectable signature in transmission high-resolution spectroscopy. In the former case, the peak of the cross-correlation would be blue-shifted, while in the latter case it would be broadened. Since the disk-averaged wind speed is expected to be small (a few km/s), these effects are comparable with the resolution of the current and planned spectrographs. The stability of the instrument profile is therefore essential in this case, and this requirement seems to be met by most of the upcoming spectrographs, as described above. The detection of rotational broadening in the line profile of the transmission spectrum of HD 189733 b is presented in Chapter 6.

7.4 The next decade: Extremely Large Telescopes

The next 5-10 years will likely see another breakthrough in the field of exoplanets, which is the discovery of terrestrial planets in the habitable zone of nearby stars. From statistical work (Kopparapu 2013; Dressing & Charbonneau 2013), we know already that 15-60% of M-dwarfs host a terrestrial planet (0.5-1.4 R_{\oplus}) in the habitable zone. The occurrence of terrestrial planets around solar-type stars is more uncertain, due to the incompleteness of radial-velocity and transit surveys. By extrapolating current statistics, about 5% of Suns should host a planets with radius within 0.5-1.4 R_{\oplus} and receiving between 1/4 and 1 solar constants (340-1360 W m⁻²).

A number of surveys is already scanning the sky looking for planets around M-dwarfs (MEarth South/North, SPECULOOS, ExTrA, APACHE). Moreover, other planned surveys aim to find planets orbiting the brightest stars. The all-sky survey MASCARA (Snellen et al. 2013a) will come online in the next months, and will monitor stars down to V = 8 mag. The TESS space mission, which is supposed to be launched in 2017, will monitor stars 30-100 times brighter than the sample of the *Kepler* mission, finding more than 3000 planets orbiting the brightest known stars, and among these ~ 500 Earth-size and super-Earth planets. This sample will be a treasure to study during the next decade. It is therefore crucial to put the next generation of ELTs in context. When these giants will be online, we will have found terrestrial planets in the habitable zones of their host stars. At that time, we will need to characterize these planets and determine with high confidence the existence of a true Earth twin. In this context, there are a number of unique advantages by observing at high resolution:

- **Characterizing bright systems:** differential (spectro-)photometry of very bright targets will be limited by the lack of comparison stars. Moreover, with ELTs the stars will saturate even for sub-second exposure times. High-resolution spectroscopy allows us to self-calibrate the data (see Chapters 2, 3, 4, and 6), so that no reference star is needed to perform the observations. Moreover, saturation will be avoided thanks to the high-dispersion of the starlight. These will be enormous advantages for studying the sample of the brightest and closest exoplanets;
- **O**₂ **in terrestrial planets around M-dwarfs:** Snellen et al. (2013b) pointed out that the high-resolution transmission signal of molecular oxygen in the A-

band (0.76 μ m) relative to the continuum of an M-dwarf is only a factor of ~ 3 weaker than the CO dayside signal detected in τ Boötis b. The big difference is that τ Boötis is a K = 3.4 mag star, while the most likely *I*-magnitude of the nearest M-dwarf hosting a terrestrial planet will be 10-12. This means that, With the E-ELT and a UVES-like spectrograph, we will need 10-50 transit to reach a detection with a S/N = 5. Given the probability of observing such transits from one single location on Earth, this will take between 4 and 20 years to be reached. Feasible, but challenging;

- **Phase curves:** thanks to the high collecting power of the ELTs, it will be possible to study how the cross-correlation signal varies as function of planet orbital phase. While broad-band phase curve detect the change in the planet continuum emission while the night- and the day-side come in and out of view, at high-resolution phase curves would measure the change in the depth of the spectral lines. For the most irradiated exoplanets, the atmospheric lapse rate could be steeper on the night side than on the dayside (Showman et al. 2009), producing a stronger detected signal (de Kok et al. 2014). Therefore, phase curves at low and high resolution carry complementary information about the planet atmospheres. They can constrain the planet albedo, recirculation efficiency, and the change in the planet *T*/*p* profile during the course of a full day;
- **True planet line spectra:** for the brightest hot Jupiters, the signal provided by an ELT will be enough to detect the planet spectrum directly by shifting the spectra to the planet rest frame and summing them in time, without the need of the cross-correlation. This will finally allow us to measure the true line-by-line spectrum of an exoplanet, without relying on atmospheric models;
- Winds: the combination of an extremely large telescope and an extremely high-resolution spectrograph could in principle resolve the vertical wind pattern in hot-Jupiter atmospheres. Based on our model planet spectra, the molecular lines of hot giant planets start to be resolved at a spectral resolution of 2-3×10⁵. Since the wind speed and direction can change as a function of atmospheric pressure, it is in principle possible to measure these changes by looking for asymmetries in the line profile from the core to the wings. For example, a strong jet wind at high altitude and a relatively calm atmosphere at the level of the photosphere would produce a skewed line profile.
- Combining high spatial and spectral resolution: direct imaging techniques only recently started to couple high spatial contrast with low-resolution spectroscopic capabilities, in order to better suppress speckle noise. We have designed and recently tested a way to couple high-contrast imaging with highresolution spectroscopy. In this way, the typical star/planet contrast achievable in imaging (10^4 - 10^5) can be coupled to the typical contrast we achieve by spectral separation plus cross-correlation ($1-2 \times 10^5$ at 1σ), bringing the detectable star/planet contrast to 10^8 or more. The ideal way of performing this combination would be to couple integral field units with high resolution spectrographs,

a solution which is planned already for the METIS instrument at the E-ELT. We tested the method with CRIRES at the VLT, by aligning the slit with the star β Pic and its planet companion. With only 1 hours of integration time, we were able to detect the planet signal in the form of CO absorption at 2.3 μ m, at a S/N of 7 (Snellen et al. *Nature*, accepted). Furthermore, we detected a broadening in the line profile consistent with a rotational period of about 8 hours.

7.5 Final remarks

The technique presented in this thesis represents a breakthrough in exoplanet characterization. It allows us to access the atmospheres of close-in, non-transiting bodies, and to unambiguously assess the presence of molecular species, which is a fundamental requirement of future searches for biomarkers. Moreover, high-resolution spectroscopy does not need a reference star, which makes it a powerful method to apply to bright systems, which will also be the easiest to characterize. It will allow to maximize the yield of future missions searching for planets around the brightest and nearest stars, such as the TESS mission. Finally, in combination with the next generation of ELTs, high-resolution spectroscopy will enable unique and exciting science cases, ranging from the direct detection of wind patterns through their Doppler signature to the two-dimensional surface mapping of the brightest directly-imaged planets, similarly to the recent work on the brown dwarf Luhman 16-B (Crossfield et al. 2014).

In this final Chapter, we have also presented the major challenges of this method, in particular the lack of broad-band spectral information and measurements of absolute fluxes, which impact the estimate of absolute molecular abundances and of the continuum temperature. We have suggested that one way of improving these observations would be to pair low-resolution and high-resolution spectroscopy. This implies the development of new retrieval algorithms capable to treat the information from both types of observations, which is currently missing.

In conclusion, high-dispersion observations from the ground have just started to show their potential, and a broader interest from the community is desirable for bringing the technique to maturity and make it ready for the next generation of telescopes and for the sample of bright, nearby planets which will be available in 5-10 years from now.

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