Infrared spectroscopy of exoplanets: observational constraints

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The exploration of transiting extrasolar planets is an exploding research area in astronomy. With more than 400 transiting exoplanets identified so far, these discoveries have made possible the development of a new research field, the spectroscopic characterization of exoplanets’ atmospheres, using both primary and secondary transits. However, these observations have been so far limited to a small number of targets. In this paper, we first review the advantages and limitations of both primary and secondary transit methods. Then, we analyse what kind of infrared spectra can be expected for different types of planets and discuss how to optimize the spectral range and the resolving power of the observations. Finally, we propose a list of favourable targets for present and future ground-based observations.

1. Introduction

The exploration of extrasolar planets is an exploding research area in astronomy. Sixteen years after the first detection of an exoplanet around a solar-type star, more than 1000 objects have been detected. While the first detections were achieved by the radial velocimetry technique, more and more exoplanets (presently over 400) have been identified through the transit method, using both ground-based surveys and dedicated space missions. Following the pioneering work of CoRoT, the Kepler mission has reached a major achievement in the detection of transiting planets, identifying thousands of possible candidates and opening the possibility of detecting super-Earths in the habitable zone of their host stars [1].

These new discoveries have made possible the development of a new research field, the spectroscopic characterization of the exoplanets’ atmospheres. In the first step, primary transits were considered, when the
planet crosses the star in front of it. The absorbed light of the planetary limb, observed at the
terminator in front of the stellar background at different wavelengths, provides information
about the atmospheric composition of the planet at the terminator. Results were first obtained
in the visible with the detection of Na I [2], then in the UV with the detection of an extended
exosphere [3]. Evidence for haze was derived from the visible spectrum, using the Hubble
Space Telescope (HST) [4]. The infrared range, mainly explored with the HST and Spitzer, offers
the possibility of probing the neutral atmospheres of the exoplanets and identifying molecular
species [5–9].

Secondary transits, corresponding to the occultation of the planet by the star, have also been
used for characterizing planetary atmospheres. In this case, the emission spectrum of the planet
is observed on the dayside. Space data have been obtained with the HST/NICMOS and with
Spitzer. Many articles have been published, leading to the identification of H2O, CH4, CO and
CO2 [10–12]. References relating to primary and secondary transit spectroscopy results prior to
2011 can also be found in [13].

So far, transit spectroscopy observations have been mainly focused on two bright exoplanets,
HD189458b and HD189733b. Spectra of other transiting objects (GJ 436b, XO-1b, GJ 1214b,
XO-2b, WASP-12b) have also been reported. Spectroscopic observations using both primary and
secondary transits will doubtless develop in the coming decade. Both techniques have their
specific advantages and are thus complementary.

In this paper, we first review the advantages and limitations of both primary and secondary
transit methods (§2). Then, starting from our experience of Solar System planets, we investigate
the possible nature of infrared spectra of exoplanets for a wide variety of objects, on the basis
of their masses, radii, distances to their host stars and the spectral type of those stars (§3). In
§4, we analyse the two components (reflected/scattered and thermal) of the infrared spectra
for various types of exoplanets and investigate the optimum spectral range and resolving power
for characterizing their atmospheres. In §5, we discuss how to identify the most promising
targets for present and future ground-based observations. Conclusions are summarized in §6.

2. Primary and secondary transits

The transit phenomenon takes place when a celestial body, as seen from the Earth, crosses the path
of a more distant object with an angular diameter larger than its own. In the solar system, we are
familiar with solar eclipses by the Moon, Venus or Mercury. The same phenomenon can take place
in the case of exoplanets if the Earth is close to the orbital plane of the exoplanet. When the planet
passes in front of the star, the event is called a primary (or direct) transit; when it passes behind
the star, it is called a secondary (or indirect) transit or an eclipse or, more properly, an occultation.
In both cases, the information on the exoplanet’s atmosphere is retrieved from the flux difference
of the (star + planet) system before and/or after the transit, and during the transit.

(a) Primary transits

When a planet passes in front of its host star, the star flux is reduced by a couple of percent or less;
the radius of the planet can be inferred from this measurement. If atomic or molecular species are
present in the exoplanet’s atmosphere, the inferred radius is smaller at some specific wavelengths,
because of the absorption in the exoplanet’s atmosphere owing to the spectral signatures of these
species. The area of planetary atmosphere observed in transmission is an annulus around the
planet with a radial height of about 5 × H, where H is the scale height [14]. H is equal to RT/μg,
where R is the perfect gas constant, T the temperature, μ the mean molecular weight of the
atmosphere and g the planet’s gravity. The amplitude of the absorption within the exoplanet’s
atmosphere can be approximated as

\[ A = 5 \times \left[ \frac{2R_p H}{R^*} \right] \],

where \( R_p \) and \( R^* \) are the radii of the planet and the star, respectively [14].
For a hydrogen–helium-rich planet with \( \mu = 2.4 \), the scale height (km) can be expressed as

\[
H = 3.46 \times \frac{T}{g}, \tag{2.2}
\]

where \( T \) is the temperature in kelvins and \( g \) is the gravity in m s\(^{-2}\). The gravity \( g \) can be expressed as

\[
g = 25 \times \frac{M_P}{R_P^2}, \tag{2.3}
\]

where \( M_P \) and \( R_P \) are the mass and the radius of the planet, expressed in Jovian masses and radii, respectively. As a result, the amplitude of the absorption can be written (with \( R^* \) expressed in solar radii) as

\[
A = 1.4 \times 10^{-6} \times R_P \times \frac{H}{R^*}. \tag{2.4}
\]

For hot Jupiters, typical values of \( A \) are a few \( 10^{-4} \). Equation (2.4) shows that the \( A \) signature is especially strong for planets having a high temperature (and thus being close to their stars), a large radius and a low molecular weight. Inflated hot Jupiters are thus privileged targets for primary transits.

Primary transits probe the exoplanet’s atmosphere in a specific diurnal configuration, which exactly corresponds to the terminator (both morning and evening sides). In the case of hot Jupiters, expected to be tidally locked, this observation is of special interest for probing possible sub-stellar to anti-stellar winds, as observed, on a much lower scale, in the case of the Venus mesosphere. Primary transit spectroscopy has the advantage of a simple identification of the atmospheric constituents, as all species are observed in absorption along the line of sight. Information is retrieved on their column densities, i.e. on their partial pressures at a given atmospheric level corresponding to an optical depth of unity. By contrast, there is no absolute measurement of the molecular abundances.

Most primary transit results have been obtained on two bright hot Jupiters, HD209458b and HD189733b, using mainly the HST and Spitzer space observatory [2–7]. Ground-based observations have led to the detection of Na [15] and CO in HD209458b using high-resolution ground-based observations at 2.3 \( \mu \)m [16]. Another significant result is the featureless spectrum of GJ 1214b at 0.7–1.0 \( \mu \)m, implying a metal-rich atmosphere [17].

(b) Secondary transits

Unlike primary transits, secondary transits provide us with a direct detection of the planet’s emission. Also in contrast with the previous case, the planet is observed on the dayside, which makes the two methods fully complementary.

The observability of secondary transit spectra depends upon the planet-to-star flux ratio. To begin with, over a broad spectral range in the visible and near-infrared, this ratio \( \rho \) can be approximated using Stefan’s law:

\[
\rho 1 = \left[ \frac{R_P^2}{R^*} \right]^2 \left[ \frac{T^4_e}{T^*} \right], \tag{2.5}
\]

where \( T^* \) is the effective temperature of the star and \( T_e \) the equilibrium temperature of the planet. In the case of a tidal-locked planet (as expected for hot Jupiters), this equilibrium temperature can be inferred from the fraction of stellar energy absorbed by the planet:

\[
\left[ \frac{F^*}{D^2} \right] (1 - a) = 2\sigma T^4_e, \tag{2.6}
\]

where \( a \) is the albedo, \( D \) is the star–planet distance, \( F^* \) is the stellar flux (proportional to \( R^*^2 \) and \( T^*^4 \)) and \( \sigma \) is Stefan’s constant. In the case of hot Jupiters, a low albedo can be assumed, as an effect of Rayleigh/Mie scattering; in what follows, we adopt the typical value of 0.03 (see §3). The
\( \rho \) factor decreases as \( D^{-2} \) and, again, is most favourable for hot Jupiters. We note that, in the case of primary transits, if we approximate the planet’s temperature with its equilibrium temperature \( T_e \), the dependence of the transmission signature varies as \( D^{-1/2} \), i.e. not as fast as the thermal emission. Spectroscopy of primary transits of distant planets should thus be, \textit{a priori}, less difficult than emission spectroscopy [14].

As will be discussed below (§4), the visible and infrared spectra are dominated by thermal emission over the whole spectral range. In the mid-infrared, the \( \rho \) ratio can be approximated using the Rayleigh–Jeans approximation of the blackbody spectrum (\( h\nu \ll kT \))

\[
\rho 2 = \left[ \frac{R_P^2}{R^*} \right] \times \left[ \frac{T_e}{T^*} \right] = 0.01 \times \left[ \frac{R_P^2}{R^*} \right] \times \left[ \frac{T_e}{T^*} \right], \tag{2.7}
\]

where \( R_P \) and \( R^* \) are expressed in Jovian and solar radii, respectively. For hot Jupiters, estimates of \( \rho 1 \) and \( \rho 2 \) are in the range of a few \( 10^{-4} \) (equation (2.5)) and a few \( 10^{-3} \) (equation (2.7)), respectively. These equations show that, as for primary transits, hot and big Jupiters are favoured. In addition, there are two ways by which the \( \rho \) factor can be enhanced: (i) using M-type stars, which have intrinsic low luminosities and (ii) observing at mid-infrared wavelengths, as the planet/star flux ratio increases towards the infrared (see §4).

In the thermal regime, molecular signatures can appear in emission or absorption, depending upon the gradient of the temperature profile, and their interpretation is thus more complex, as it requires the simultaneous retrieval of the temperature vertical distribution. As in the case of primary transits, most of the results have been obtained on HD209458b and HD189733b, using HST and Spitzer space data [8–12]. On HD189733b, thermal emission has also been detected using ground-based spectroscopy at IRTF [18,19].

### 3. Infrared spectroscopy of transiting exoplanets

In what follows, we try to estimate the spectroscopic detectability of a transiting exoplanet on the basis of its mass, its distance to its host star and the spectral type of this star. Three classes of mass are considered [20]: Jupiters \( (M > 20 M_E) \), Neptunes \( (10–20 M_E) \) and Small Exos \( (M < 10 M_E) \) and three classes of temperatures: hot \( (800 < T < 2000 \text{ K}) \), warm \( (350–800 \text{ K}) \) and temperate \( (250–350 \text{ K}) \). The limit of \( 10 M_E \) is chosen with reference to the core accretion model of planetary formation: it is the typical threshold between solid bodies, with little or no atmospheric contribution in their mass, and gaseous planets, formed from a core with a gravity field sufficient to capture the protostellar gas, namely hydrogen and helium [21].

As described in equation (2.6), the equilibrium temperature \( T_e \) of the exoplanet is defined as the temperature of the blackbody that emits the same quantity of absorbed stellar flux. Equation (2.6) corresponds to the case of a slow rotator (or phase-locked object) and can also be written as follows \( (T_e \text{ and } T^* \text{ are in kelvins, } D \text{ is in AU and } R^* \text{ in solar radii})\):

\[
T_e = (1 - a)^{0.25} \times 331.0 \times \left[ \frac{T^*}{5770.0} \right] \times \left[ \frac{(R^*)^{0.5}}{D^{0.5}} \right]. \tag{3.1}
\]

The equation becomes as follows for a fast-rotating planet:

\[
T_e = (1 - a)^{0.25} \times 279.0 \times \left[ \frac{T^*}{5770.0} \right] \times \left[ \frac{(R^*)^{0.5}}{D^{0.5}} \right]. \tag{3.2}
\]

In what follows, we adopt equation (3.1) for planets located within the tidal-lock limit. The critical distance for tidal lock is about 0.5 AU for a solar-type star and is proportional to \( [M^*]^{1/3} \) for a star of mass \( M^* \) [21]. We adopt equation (3.2) in the case of planets located beyond this limit.

The albedo is unknown in the case of most exoplanets. A typical value for Solar System planets is 0.3; other Solar System objects range from about 0.04 (comets) to 0.10–0.20 (asteroids and trans-Neptunian objects), with some brighter objects like Saturn’s satellite Enceladus \( (a > 0.9) \). In what follows, we adopt the following values for the albedo [22]: \( a = 0.03 \) for hot and warm Jupiters.
Table 1. Equilibrium temperatures of exoplanets. The equilibrium temperature $T_e$ (in K) of an exoplanet is calculated as a function of the star–planet distance for different spectral types of the host star. Two values of the albedo are assumed, $a = 0.3$ (upper line) and $a = 0.03$ (lower line). An albedo of 0.3 corresponds to Small Exos and to temperate Jupiters and Neptunes; $a = 0.03$ corresponds to hot and warm Jupiters and Neptunes (see §3). For distances of 0.05 and 0.1 AU, $T_e$ is calculated for synchronous rotation and refers to the dayside hemisphere of the planet. At larger distances, $T_e$ is calculated for a fast-rotating planet. The table is adapted from [23].

<table>
<thead>
<tr>
<th>Distance to the star (AU)</th>
<th>0.05</th>
<th>0.1</th>
<th>1</th>
<th>5</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ($T^* = 10000$ K)</td>
<td>3315</td>
<td>2344</td>
<td>625</td>
<td>279</td>
<td>140</td>
</tr>
<tr>
<td>$R^* = 2.0 R_{\text{sol}}$</td>
<td>3598</td>
<td>2544</td>
<td>678</td>
<td>303</td>
<td>152</td>
</tr>
<tr>
<td>F ($T^* = 7000$ K)</td>
<td>1516</td>
<td>1072</td>
<td>339</td>
<td>152</td>
<td>76</td>
</tr>
<tr>
<td>$R^* = 1.2 R_{\text{sol}}$</td>
<td>1645</td>
<td>1163</td>
<td>368</td>
<td>164</td>
<td>82</td>
</tr>
<tr>
<td>G ($T^* = 5770$ K)</td>
<td>1353</td>
<td>956</td>
<td>255</td>
<td>114</td>
<td>57</td>
</tr>
<tr>
<td>$R = 1.0 R_{\text{sol}}$</td>
<td>1468</td>
<td>1038</td>
<td>277</td>
<td>124</td>
<td>62</td>
</tr>
<tr>
<td>K ($T^* = 4200$ K)</td>
<td>693</td>
<td>490</td>
<td>155</td>
<td>69</td>
<td>34</td>
</tr>
<tr>
<td>$R^* = 0.7 R_{\text{sol}}$</td>
<td>752</td>
<td>532</td>
<td>168</td>
<td>75</td>
<td>37</td>
</tr>
<tr>
<td>M ($T^* = 3200$ K)</td>
<td>344</td>
<td>243</td>
<td>77</td>
<td>34</td>
<td>17</td>
</tr>
<tr>
<td>$R^* = 0.3 R_{\text{sol}}$</td>
<td>373</td>
<td>264</td>
<td>84</td>
<td>37</td>
<td>19</td>
</tr>
</tbody>
</table>

and Neptunes (the low albedo is assumed to be owing to Rayleigh or Mie scattering); $a = 0.3$ for temperate Jupiters and Neptunes (reflection above a cloud surface is assumed) and for all Small Exos (reflection above the surface is assumed).

Table 1 gives the expected equilibrium temperatures at various distances from the stars for different spectral types [23]. Two values are assumed for the albedo, $a = 0.3$ and $a = 0.03$. For distances of 0.05 and 0.1 AU, we calculate the equilibrium temperatures corresponding to synchronous rotation. For larger distances, we assume fast-rotating objects. The equilibrium temperatures differ by a factor of $2^{0.25}$ (1.189).

4. The infrared spectrum of an exoplanet: how to optimize the spectral range and resolving power

The infrared spectrum of an exoplanet is composed of two main components: the reflected/scattered stellar flux, which peaks in the UV, visible or near-infrared range (depending on the spectral type of the host star), and the thermal emission which dominates at longer wavelengths. In the first case, molecular signatures appear in absorption in front of the stellar background (the same mechanism applies in the case of primary transit observations). By contrast, in the thermal regime, the emitted flux refers to the temperature of the emitting layer. If the thermal profile decreases monotonically as the altitude increases (as in the case of Mars and Venus), molecular signatures appear in absorption. If a temperature inversion is present, i.e. if the exoplanet exhibits a stratosphere (as in the case of the Earth, giant planets and Titan), the molecular features can appear in emission (in the stratosphere) or in absorption (in the troposphere), depending on the atmospheric level where the lines are formed. Because we have no a priori information about the thermal profile of the exosphere, it is important to identify the wavelength range where each component (reflected or thermal) dominates.

Figure 1 shows the two components (in the form of blackbody curves) for (i) the two most-studied hot Jupiters and (ii) the warm object GJ 1214b. It can be seen that for the two hot Jupiters, the thermal emission dominates at all wavelengths above 1 μm. For GJ 1214b, the crossover is between 2.5 and 4 μm, depending on the value of the albedo. In the case of temperate objects.
adjacent Main molecular signatures and constraint on the spectral resolving power. Table 2. planet–stardistance, fast rotation is assumedin all cases. The figure is adapted from [23]. (Online version in colour.)

thermal regime, one needs to infer simultaneously the thermal profile and the vertical profiles of species, as only column densities are inferred. In the component, the identification is easier (as all features appear in absorption), but no information is retrieved on the vertical distributions of species, as only column densities are inferred. In the thermal regime, one needs to infer simultaneously the thermal profile and the vertical profiles of the atmospheric species. Combining the analysis of both components, whenever feasible, will be

Figure 1. Reflected/scattered components and thermal components of exoplanets’ spectra: (a) HD209458b and HD189733b, calculated for an albedo of 0.03; (b) GJ1214b, calculated for two values of the albedo, $a = 0.03$ and $a = 0.3$. In view of the small planet–star distance, fast rotation is assumed in all cases. The figure is adapted from [23]. (Online version in colour.)

Table 2. Main molecular signatures and constraints on the spectral resolving power. $\Delta \nu$ is the spectral interval between two adjacent $J$-components of a band. $S_{\text{max}}$ is the intensity of the strongest band available in the spectral interval. $R$ is the spectral resolving power required to separate two adjacent $J$-components ($\Delta \nu$). The table is adapted from [23].

<table>
<thead>
<tr>
<th>molecule</th>
<th>$\Delta \nu = 2B_0$ cm$^{-1}$</th>
<th>$\lambda$ ($S_{\text{max}}$) 2–5 $\mu$m</th>
<th>$S_{\text{max}}$ cm$^{-2}$ am$^{-1}$</th>
<th>$R$ 2–5 $\mu$m</th>
<th>$\lambda$ ($S_{\text{max}}$) 5–16 $\mu$m</th>
<th>$S_{\text{max}}$ cm$^{-2}$ am$^{-1}$</th>
<th>$R$ 5–16 $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>29.0</td>
<td>2.69 ($\nu_1, \nu_3$)</td>
<td>200</td>
<td>130</td>
<td>6.27 ($\nu_2$)</td>
<td>250</td>
<td>55</td>
</tr>
<tr>
<td>HD$_3$</td>
<td>18.2</td>
<td>3.67 ($\nu_1, 2\nu_2$)</td>
<td>270</td>
<td>150</td>
<td>7.13 ($\nu_2$)</td>
<td>140</td>
<td>130</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>10.0</td>
<td>3.31 ($\nu_2$)</td>
<td>300</td>
<td>300</td>
<td>7.16 ($\nu_4$)</td>
<td>140</td>
<td>130</td>
</tr>
<tr>
<td>CH$_3$D</td>
<td>7.8</td>
<td>4.54 ($\nu_2$)</td>
<td>25</td>
<td>280</td>
<td>8.66 ($\nu_6$)</td>
<td>119</td>
<td>150</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>20.0</td>
<td>2.90 ($\nu_2$)</td>
<td>13</td>
<td>170</td>
<td>10.33, 600</td>
<td>102</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>3.00 ($\nu_1$)</td>
<td></td>
<td>20</td>
<td></td>
<td>10.72 ($\nu_2$)</td>
<td>82</td>
<td>110</td>
</tr>
<tr>
<td>PH$_3$</td>
<td>8.9</td>
<td>4.30 ($\nu_1, \nu_3$)</td>
<td>520</td>
<td>260</td>
<td>8.94 ($\nu_4$)</td>
<td>102</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.08 ($\nu_2$)</td>
<td>82</td>
<td>110</td>
</tr>
<tr>
<td>CO</td>
<td>3.8</td>
<td>4.67 (1–0)</td>
<td>241</td>
<td>565</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1.6</td>
<td>4.25 ($\nu_1$)</td>
<td>4100</td>
<td>1470</td>
<td>14.99 ($\nu_2$)</td>
<td>220</td>
<td>420</td>
</tr>
<tr>
<td>HCN</td>
<td>3.0</td>
<td>3.02 ($\nu_2$)</td>
<td>240</td>
<td>1100</td>
<td>14.04 ($\nu_2$)</td>
<td>204</td>
<td>240</td>
</tr>
<tr>
<td>C$_2$H$_2$</td>
<td>2.3</td>
<td>3.03 ($\nu_3$)</td>
<td>105</td>
<td>1435</td>
<td>13.7 ($\nu_5$)</td>
<td>582</td>
<td>320</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>2.3</td>
<td>3.35 ($\nu_1$)</td>
<td>538</td>
<td>2300</td>
<td>12.16 ($\nu_2$)</td>
<td>36</td>
<td>635</td>
</tr>
<tr>
<td>O$_3$</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.60 ($\nu_2$)</td>
<td>348</td>
</tr>
</tbody>
</table>

around M-type stars, the maximum of the emission lies beyond 5 $\mu$m. It is thus mandatory to extend the spectroscopic observations towards the mid-infrared for characterizing these objects. The case of M stars is indeed of special interest, as these stars represent about 90% of the total stellar population.

Both the reflected and thermal components show advantages and limitations. In the reflected component, the identification is easier (as all features appear in absorption), but no information is retrieved on the vertical distributions of species, as only column densities are inferred. In the thermal regime, one needs to infer simultaneously the thermal profile and the vertical profiles of the atmospheric species. Combining the analysis of both components, whenever feasible, will be
Figure 2. Transmission of main candidate molecules (H$_2$O, CO$_2$, CO, CH$_4$, NH$_3$) between 2 and 18 µm. Calculations use a line-by-line model with, for each gas, a pressure of 1 atm and a column density of 10 cm-amagat. (a) $T = 300$ K and (b) $T = 1200$ K. The spectral resolution is 10 cm$^{-1}$, which corresponds to a resolving power of 67 at 16 µm, 100 at 10 µm and 500 at 2 µm. The figure is adapted from [23]. (Online version in colour.)

Remote sensing of Solar System planetary atmospheres has demonstrated the interest of analysing, for a given species, different bands of various intensities. Indeed, in the thermal regime, these bands probe different atmospheric levels (with the strongest ones being formed in the upper levels) and information about the vertical structure of the atmosphere can be retrieved. Using different bands of the same species will also help in introducing redundancy and better resolving the ambiguities. Wavelengths above 2 µm are best suited for several reasons: the spectral signatures are stronger and the planet/star flux ratio increases at longer wavelengths; in addition, below 2 µm, spectroscopic data of molecules (overtone and combination bands) are much less well known, especially at high temperature. Table 2 lists strong infrared bands in the 2–18 µm range for a series of possible candidate species [23]. The first ones to be considered are H$_2$O, CH$_4$, NH$_3$, CO and CO$_2$. For completion, we also consider C$_2$H$_2$ and C$_2$H$_6$, the two main products of methane photodissociation, observed in the Solar System giant planets, PH$_3$ (observed in Jupiter and Saturn), HCN (detected on Neptune) and O$_3$ (observed on the Earth). Many weaker bands of all these species are also present, especially below 5 µm.

Figure 2 shows a synthetic absorption spectrum of the five major species (H$_2$O, CH$_4$, NH$_3$, CO and CO$_2$) calculated under the same conditions ($P = 1$ bar, column density = 10 cm-amagat). Two
temperatures are considered: $T = 300 \text{ K}$ (temperate exoplanets) and $T = 1200 \text{ K}$ (hot exoplanets). Most of the molecules exhibit at least two strong molecular bands (and, in many cases, much more), which makes possible the simultaneous observation of at least two bands of different intensities if the ($2-16 \mu\text{m}$) full range is observed. Moreover, at high temperature, the broadening of each band (owing to the increasing contribution of high $J$-value components) leads to a strong overlap of the spectral signatures, making the identification of the molecular species more difficult. Ideally, the spectral resolving power should be sufficient to separate two adjacent $J$-components of this molecule. This interval is equal to $2 B_0$, where $B_0$ is the rotational constant of the molecule. Table 2 lists the $\Delta \nu$ interval for the main bands of our list of candidate species and the resolving power required to resolve this interval [23]. It can be seen that for $\text{H}_2\text{O}$, $\text{CH}_4$ and their isotopes, as well as $\text{NH}_3$ and $\text{PH}_3$, a resolving power of 300 (below $5 \mu\text{m}$) and 150 (above $5 \mu\text{m}$) is sufficient for identifying the bands unambiguously at any temperature. Other molecules, however, require higher constraints: $R = 560$ for CO ($4.7 \mu\text{m}$); $R > 1000$ for O$_3$ ($9.6 \mu\text{m}$); $R = 420$ and 240 for CO$_2$ and HCN, respectively, in the 14–15$\mu\text{m}$ region. In summary, a resolving power of 300 over the whole ($2-16 \mu\text{m}$) spectral range should allow the unambiguous identification of at least one band of all the molecules listed above, except CO, CO$_2$, O$_3$ and hydrocarbons. However, the spectral separation of molecular bands above $5 \mu\text{m}$ is easier than at shorter wavelengths, because the confusion is less severe, and a lower resolving power can be used for identifying the main molecular bands.

5. How to select the best targets for ground-based transit spectroscopy?

So far, transit spectroscopy of exoplanets has been mainly performed on two hot Jupiters: HD209458b and HD189733b. Located at relatively close distances (47 and 19 pc, respectively), the two stars (G0V and K1-K2, respectively) have a visible magnitude $V$ of 7.7, much brighter than the host stars of the other transiting hot Jupiters. In order to search for other potential candidates, we use the list of transiting planets ranked as a function of increasing magnitude $V$. The $V$ magnitude is chosen, although infrared magnitudes would be more relevant, because, in many cases, the $K$, $L$ and $M$ magnitudes of the host stars are unknown. Using equations (2.4), (2.5) and (2.7), we select the objects showing the highest values for $A$ (primary transit) and for $\rho_1$ and $\rho_2$ (secondary transit). For the range of temperatures considered here, $\rho_1$ and $\rho_2$ give good approximations of the (planet/star) thermal flux ratio around $1 \mu\text{m}$ and beyond about $20 \mu\text{m}$, respectively. In equation (2.4), the scale height is calculated assuming for $T$ the equilibrium temperature $T_{\text{eq}}$, as calculated from equation (3.1) and a mean molecular weight of 2.4 ($\text{H}_2$–He mixture). In the case of Neptunes and Small Exos, this assumption is of course arbitrary. The $A$ value would be divided by 7.5 in the case of a water-rich atmosphere, and even more in the presence of silicate vapour (possibly relevant for Small Exos).

A few interesting objects are outlined in table 3. WASP-33b, a very hot and massive object, appears well suited for secondary transit observations. HAT-P1b, WASP-34b and WASP-13b are three hot, inflated objects, more favourable for primary transit observations. WASP-48b, WASP-17b and WASP-12b are good targets for both kinds of transits. WASP-12b, in particular, is a very hot object where CO and CH$_4$ have been tentatively identified, possibly indicating a high C/O ratio [25]; this result, however, has been questioned [26,27]. We have kept HD149026b in the list of favourable hot Jupiters, although its $A$ and $\rho$ values are not especially high, because its host star is relatively bright. HAT-P26b is a hot Neptune well suited for primary transits. Regarding Small Exos, GJ 1214b is an interesting case, with high expected values of $A$ and $\rho$, mostly owing to the very small size of its host star, an M-dwarf. Many authors have speculated about the possible composition of its atmosphere [28]. In the case of CoRoT-7b, a hot object very close to its star, we do not expect an atmosphere, except possibly silicate haze or noble gases.

We now discuss the detectability of the targets listed in table 3, with the present and future ground-based telescopes. For this purpose, we use the time calculator of the Very Large Telescope (VLT) infrared spectrometer SINFONI to estimate the signal-to-noise (S/N) ratio achievable in one observing night (one transit, or about 3 h of integration time) for the targets listed in table 3,
above (table 2), the need for such a high resolving power is not obvious (except for some specific
the spectra of the objects listed in table 4 at high resolution ( ).
observe exoplanets up to a magnitude of 14 at moderate resolution, or, alternatively, to explore
a gain in flux by a factor of over 20 or more than 3 magnitudes. It should then be possible to
IFU (HARMONI) will have performances comparable with those of SINFONI, we can anticipate
a very few cases (WASP-33b, WASP-48b). In the case of the 39 m E-ELT, assuming that the ELT-
primary transit observations. Secondary transit observations are expected to be possible only in
most of the objects are within the detectability limit of a 8 m telescope, at moderate resolution, for
and is also consistent with the CRIRES observations of HD209458b [16].

Table 4 presents that
an S/N ratio of about 50 for a resolving power of 150, in agreement with the SINFONI estimate,
and is also consistent with the CRIRES observations of HD209458b [16].

\[
\begin{array}{cccccccccc}
exoplanet & V & M_p & R_p & T_e & R^* & T^* & A & \rho_1 & \rho_2 \\
\hline
\text{hot Jupiters} & & & & & & & & & \\
HD209458b & 7.65 & 0.714 & 1.380 & 1702 & 1.146 & 6075 & 9.2 & 3.2 & 4.1 \\
HD189733b & 7.67 & 1.138 & 1.178 & 1422 & 0.788 & 4980 & 6.4 & 5.2 & 6.4 \\
HD149026b & 8.15 & 0.356 & 0.718 & 2071 & 1.497 & 6147 & 1.8 & 0.87 & 0.77 \\
WASP-33b & 8.30 & 4.590 & 1.438 & 3170 & 1.444 & 7400 & 1.9 & 7.7 & 4.2 \\
HAT-P1b & 10.40 & 0.524 & 1.217 & 1529 & 1.115 & 5975 & 8.2 & 2.0 & 3.0 \\
WASP-34b & 10.40 & 0.590 & 1.220 & 1369 & 0.930 & 5700 & 9.4 & 2.4 & 4.1 \\
WASP-13b & 10.42 & 0.460 & 1.210 & 1447 & 1.000 & 5826 & 11.0 & 1.8 & 3.0 \\
WASP-48b & 11.06 & 0.980 & 1.670 & 1921 & 1.090 & 6570 & 15.0 & 7.7 & 7.5 \\
WASP-17b & 11.60 & 0.486 & 1.991 & 1963 & 1.380 & 6650 & 32.0 & 5.4 & 6.1 \\
WASP-12b & 11.69 & 1.404 & 1.736 & 2999 & 1.599 & 6300 & 8.5 & 6.0 & 5.6 \\
\text{hot/warm Neptunes} & & & & & & & & & \\
HAT-P11b & 9.59 & 0.081 & 0.452 & 1025 & 0.750 & 4780 & 1.3 & 0.35 & 0.78 \\
GJ 436b & 10.68 & 0.074 & 0.365 & 842 & 0.464 & 3864 & 5.0 & 0.62 & 1.3 \\
HAT-P26b & 11.74 & 0.059 & 0.565 & 1174 & 0.788 & 5090 & 11.0 & 0.47 & 0.89 \\
\text{Small Exos} & & & & & & & & & \\
55CncE & 5.95 & 0.027 & 0.190 & 2122 & 0.943 & 5196 & 1.2 & 0.27 & 0.16 \\
HD97658b & 6.27 & 0.020 & 0.262 & 814 & 0.730 & 5170 & 2.6 & 0.05 & 0.20 \\
CoRoT-7b & 11.70 & 0.015 & 0.150 & 1971 & 0.870 & 5275 & 11.0 & 0.15 & 0.11 \\
GJ 1214b & 14.70 & 0.020 & 0.245 & 600 & 0.210 & 2949 & 19.0 & 1.2 & 2.8 \\
\end{array}
\]

using their A and \( \rho_1 \) values. Calculations were made at 2.175 \( \mu \)m for a resolving power \( R \) of 4000.
Results are given in table 4. We checked their consistency by using the CRIRES calculator on
HD209548b: an S/N ratio of about 2150 is found for the host star in 3 h for a resolving power of
100 000, implying an S/N ratio of about 2 on the exoplanet in primary transit. This translates into
an S/N ratio of about 50 for a resolving power of 150, in agreement with the SINFONI estimate,
and is also consistent with the CRIRES observations of HD209458b [16]. Table 4 presents that
most of the objects are within the detectability limit of a 8 m telescope, at moderate resolution, for
primary transit observations. Secondary transit observations are expected to be possible only in
a very few cases (WASP-33b, WASP-48b). In the case of the 39 m E-ELT, assuming that the ELT-
IFU (HARMONI) will have performances comparable with those of SINFONI, we can anticipate
a gain in flux by a factor of over 20 or more than 3 magnitudes. It should then be possible to
observe exoplanets up to a magnitude of 14 at moderate resolution, or, alternatively, to explore
the spectra of the objects listed in table 4 at high resolution (\( R > 10000 \)). However, as mentioned
above (table 2), the need for such a high resolving power is not obvious (except for some specific
observations measuring Doppler shifts, as in the case of the CO detection in HD209548b [16]), as
most of the spectral signatures are expected to be identified with a resolving power of about 1000
or less.

It has to be mentioned that the S/N ratio estimates listed in table 4 are expected to be
overestimated, because the exposure time calculator only takes photon noise into account and
The main conclusions of this study can be summarized as follows: with the observations and modelling of GJ 436b [29].

Table 4. Ground-based transit spectroscopy: estimates of S/N ratio for an 8 m telescope. The SINFONI/VLT time calculator is used in the K band, with an exposure time of 3 h and a resolving power of 4000. Note that the time calculator only takes into account the photon noise and assumes a perfect stability of the instrument and atmosphere, which is an optimistic assumption.

<table>
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<tr>
<th>exoplanet</th>
<th>V</th>
<th>T*(K)</th>
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<th>S/N(A) (R = 150)</th>
<th>S/N(A) (R = 50)</th>
<th>S/N(ρ=1) (R = 150)</th>
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<td>2.8</td>
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</table>

assumes a perfect stability of the instrument and the atmosphere. This explains why few spectroscopic observations have been achieved from the ground using 8 m class telescopes, even on the two brightest sources, HD209458b and HD189733b. Nevertheless, table 4 provides some information about the performances that can be expected for a variety of targets, as compared with the two brightest ones.

Figure 3 shows the molecular signatures expected to be identified in the K, L and M filters. The signatures are shown in transmission, so the comparison is relevant for primary transit observations, which show no degeneracy associated with the exoplanet’s thermal profile. In the K filter, with a resolving power of about 150, one could expect to separate CH4, NH3 and CO. CH4 is the main absorber in the L band and CO dominates the M band. These results are consistent with the observations and modelling of GJ 436b [29].

6. Conclusion

The main conclusions of this study can be summarized as follows:

— Infrared transit spectroscopy of exoplanets appears to be a promising tool for exploring exoplanets’ atmospheres; primary transit observations are especially suited for observing hot inflated Jupiters, while hot and massive objects around low-mass stars are favoured targets for secondary transits.
Figure 3. Molecular signatures expected in the K, L and M filters. The transmission is calculated as in figure 2, with a spectral resolution of $33 \text{ cm}^{-1}$ ($R = 150$ at 2 $\mu$m and 75 at 4 $\mu$m). These conditions are appropriate for ground-based observations with an 8 m telescope (see table 4). (Online version in colour.)

— At high temperatures ($T > 1000$ K), molecular signatures become very broad and complex. Still, a resolving power of a few hundred should be adequate for resolving most of the spectral signatures of the candidate molecules over the whole infrared range.

— Near-infrared transit spectroscopy of a few hot exoplanets, especially during primary transits, should be achievable at moderate resolution ($R = 50–150$) with an 8 m class telescope. A flux gain by a factor of over 20, or 3 magnitudes, is expected with the E-ELT.

— Exploring the atmospheres of temperate objects around M-dwarfs will require spectroscopic measurements over the whole infrared range, ideally up to 16 $\mu$m, and will take advantage of dedicated space programmes (JWST, EChO).

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