EPSC Abstracts
Vol. 8, EPSC2013-817-1, 2013
European Planetary Science Congress 2013

Molecular Detectability in Exoplanetary Emission Spectra

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Abstract

Of the many recently discovered worlds orbiting distant stars, very little is yet known of their chemical composition. With the arrival of new transit spectroscopy and direct imaging facilities, the question of molecular detectability as a function of signal-to-noise (SNR), spectral resolving power and type of planets has become critical. We study the detectability of key molecules in the atmospheres of a range of planet types, and report on the minimum detectable abundances at fixed spectral resolving power and SNR. The planet types considered — hot Jupiters, hot super-Earths, warm Neptunes, temperate Jupiters and temperate super-Earths — cover most of the exoplanets characterisable today or in the near future. We focus on key atmospheric molecules, such as CH4, CO, CO2, NH3, H2O, C2H2, C2H6, HCN, H2S and PH3.

1. Introduction

The exoplanet field has been evolving at an astonishing rate: nearly a thousand planets have been detected and twice as many are awaiting confirmation. Astronomers have begun classifying these planets by mass, radius and orbital parameters, but these numbers tell us only part of the story as we know very little about their chemical composition. Spectroscopic observations of exoplanet atmospheres can provide this missing information, critical for understanding the origin and evolution of these far away worlds. At present, transit spectroscopy and direct imaging are the most promising methods to achieve this goal. Ground and space-based observations (VLT, Keck, IRTF, Spitzer, and the Hubble Space Telescope) of exoplanets have shown the potentials of the transit method: current observations of hot gaseous planets have revealed the presence of alkali metals, water vapour, carbon monoxide and dioxide and methane in these exotic environments. However, the instruments used in the past ten years were not optimised for this task, so the available data are mostly photometric or low resolution spectra with low signal to noise. Additionally, multiple observations are often required, during which many effects can alter the signal: from the weather on the planet to other sources of noise including instrument systematics and stellar variability. The interpretation of these — often sparse — data is generally a challenge.

With the arrival of new facilities such as Keck/GPI, VLT/SPHERE, E-ELT and *JWST*, and possibly dedicated space instruments such as *EChO* [1, 2], many questions need to be tackled in a more systematic way. Among these stands out the question of molecular detectability: *what are the objective criteria that need to be met to claim a molecular detection in an exoplanet?* In this paper we aim to address this question by focusing on the signatures of a selection of key molecules, with a range of abundances, over a broad wavelength range (1 to 16 μm). To capture the extent of possible chemical compositions of exoplanet atmospheres, we have chosen five planetary cases: hot Jupiter, hot super-Earth, warm Neptune, temperate Jupiter and temperate super-Earth [3].

2. Results

In Figure 1 we show the most intuitive and conservative approach to assess detectability: we measure in every bin the difference between the planetary signal with or without the absorption of a selected molecule. We claim a detection if a difference of at least 3-sigma is found between the continuum and the molecular signature in a given bin. While the depth of the feature will depend on the abundance of the molecule (at fixed thermal profile), the SNR in that bin will determine the value of sigma. We present in our results the minimum molecular abundance detectable as a function of fixed SNR_p=5, 10 or 20 and wavelength. In this way, our results are completely independent from the duration of the observations and the instrument design. If the departure from the continuum is less than 3-sigma, we cannot claim a detection.

Table 1 shows the calculated minimum detectable abundances for a warm Neptune planet similar to

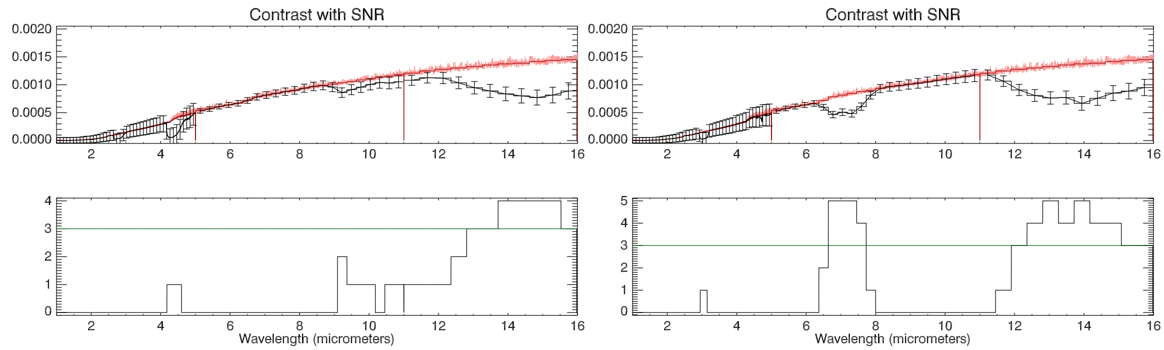

Figure 1: Detecting the presence of a molecule in the atmosphere of a Warm Neptune. The upper panels show contrast spectra where two different molecules absorb. The error bars are computed with fixed SNR$_p$=10. *Left:* CO_2 with mixing ratio=10^{-5}, *Right:* HCN with mixing ratio=10^{-4}. The planet continuum is shown in red. The lower panels show the departure of the molecular signal from the continuum in units of sigma. A 3-sigma departure is required to claim a detection. This threshold is shown here as the green horizontal line.

GJ-436b, as a function of (fixed) SNR$_p$. For most molecules, SNR$_p$=5 is enough to detect spectral signatures of most molecules, provided the molecule is present in sufficient abundances. In some cases, SNR$_p$=10 or higher may be required. Similar calculations are performed for the other planet types (hot Jupiter, hot super-Earth, temperate Jupiter, temperate super-Earth), for alternative temperature/pressure profiles, and further calculations are completed with the presence of water vapour in the atmosphere. In addition, we use more advanced methods to estimate detectability by using the likelihood ratio test to combine information from multiple bins and multiple features; this method shows an overall improvement in detection sensitivity.

	CH_4		CO		CO_2			PH_3	
SNR	3 μm	8 μm	2.3 μm	4.6 μm	2.8 μm	4.3 μm	15 μm	4.3 μm	10 μm
20	10^{-7}	10^{-6}	10^{-4}	10^{-6}	10^{-7}	10^{-7}	10^{-7}	10^{-7}	10^{-6}
10	10^{-7}	10^{-6}	10^{-3}	10^{-5}	10^{-6}	10^{-7}	10^{-6}	10^{-7}	10^{-6}
5	10^{-7}	10^{-5}	10^{-3}	10^{-4}	10^{-6}	10^{-7}	10^{-5}	10^{-7}	10^{-5}

	NH_3			HCN			H_2O		
SNR	3 μm	6.1 μm	10.5 μm	3 μm	7 μm	14 μm	2.8 μm	5 - 8 μm	11 - 16 μm
20	10^{-6}	10^{-6}	10^{-6}	10^{-7}	10^{-5}	10^{-7}	10^{-6}	10^{-6}	10^{-5}
10	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-5}	10^{-6}	10^{-6}	10^{-5}	10^{-4}
5	10^{-6}	10^{-5}	10^{-5}	10^{-6}	10^{-4}	10^{-5}	10^{-5}	10^{-5}	10^{-4}

	C_2H_6		H_2S			C_2H_2		
SNR	3.3 μm	12.2 μm	2.6 μm	4.25 μm	8 μm	3 μm	7.5 μm	13.7 μm
20	10^{-6}	10^{-6}	10^{-5}	10^{-4}	10^{-4}	10^{-7}	10^{-5}	10^{-7}
10	10^{-5}	10^{-5}	10^{-5}	10^{-4}	10^{-3}	10^{-7}	10^{-4}	10^{-6}
5	10^{-5}	10^{-5}	10^{-4}	10^{-3}	-	10^{-7}	10^{-3}	10^{-5}

Table 1: Warm Neptune: Minimum detectable abundance at fixed SNR=5, 10 and 20 for the 10 considered molecules.

3. Summary and Conclusions

With this work we address the question of molecular detectability in exoplanet atmospheres, for a range of key planet types and key molecules. We use a conservative and straightforward method, and find that for all planet cases, SNR$_p$=5 is typically enough to detect the strongest feature in most molecular spectra, provided the molecular abundance is large enough. Other detection methods, such as the likelihood ratio test, combine information from multiple spectral bins and features, and improve overall performance in detection sensitivity of ~ 10. Our analysis shows that the detectability of key molecules in the atmospheres of a variety of exoplanet cases is within realistic reach, even with low SNR and spectral resolution values.

References

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