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Detection of Earth-like atmospheres by transit spectroscopy: exploring instrumental parameters for optimal yield

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Abstract

Earth-like exoplanets represent the most challenging but also the most intriguing targets for atmospheric characterisation by transit spectroscopy. We examine optimal instrumental parameters for successful detection of atmospheric spectral signatures at an SNR of 5 or more. We calculate the signals of spectral features from an Earth-like atmosphere and design a generic spectrograph optimized to detect such an Earth-like spectrum, coupled to a simulated space-based telescope. We vary the primary mirror size of the telescope, as well as exosystem parameters and simulate both photon noise and instrumental noise. From these data, coupled with current exoplanet and stellar statistics, we can derive conclusions about optimal instrumental parameters for detection of Earth-like atmospheres and direct the design of a possible future mission to address the discovery of the f_l parameter of the Drake equation.

1. Introduction

Here we consider "Earth-like" planets to be Earth-sized planets in the habitable zones of their stars. Their small radii coupled with a compact low scale height atmosphere with high molecular weight species results in a low amplitude signal for the detection of ro-vibrational spectral bands of key atmospheric molecules. Biomarker molecules e.g. oxygen/ozone (especially in a reducing environment) may indicate the presence of life, and if a sufficient number of planets are sampled, a statistical inference can be made regarding the frequency of life on such planets. Previous studies have generally focused on the performance of a single instrument, often with fixed target. Few have considered the effects of instrumental noise factors that may be critical to consider for such low signal targets. To our knowledge this is the first study to attempt to address the question of actively designing a mission to discover the parameter f_l in the Drake equation [1]:

$$N = R_\star \cdot f_p \cdot \eta_e \cdot f_l \cdot f_i \cdot f_c \cdot L \quad (1)$$

Where N is the number of communicating civilizations, $R_\star$ is the rate of star formation, f_p is the fraction of stars with planets, η_e is the frequency of terrestrial planets in the habitable zone, f_l is the frequency of life on those planets, f_i is the fraction with intelligent life, f_c is the fraction with technological life, and L is the lifetime of the civilization. In this study we start by finding relationships between telescope/instrumental parameters such as primary mirror size and the SNR to detect biomarkers for different types of exosystems and at different distances. We then utilize knowledge of current planet and stellar statistics to infer a likely yield of observation for each observatory.

2. Generic instrumental design

A generic spectrograph is designed specifically for the detection of biomarkers. By analysing the model spectrum for an Earth-twin orbiting an M dwarf produced by [2], we establish the required spectral resolving power, R, for such an instrument if it were to detect features from an Earth-like spectrum assuming two spectral samples per full-width half-maximum (FWHM) of each feature being sampled (Table 1). Many key spectral features can be identified at $R \sim 35$, though complete characterisation would require an R of $\sim$ 100. We then couple this spectrograph to a simulated common optics assembly with a variable primary mirror area, A_{tel}. The telescope and instrument model is then applied to ExoSim [3], a generic transit spectroscopy and instrument simulator. Fig. 1 shows the result of noiseless ExoSim simulations using the planet spectrum from [2] binned to R = 35 and R = 100. The 9.6 μm O_3 feature can be easily identified at R = 35.

3. Signal modelling

We calculate the typical signal for a spectral feature of an Earth-like planet orbiting in the habitable zones of

Table 1: Spectral resolving power, R, required to sample spectral features.

Species	Mid-wavelength (µm)	FWHM (µm)	Minimum R
O_2	0.76	0.034	45
O_2	1.26	0.027	92
H_2O	1.4	0.095	30
$CO_2{}^a$	2	0.114	35
CH_4	2.35	0.138	34
$CO_2{}^b$	2.7	0.153	35
$CH_4{}^c$	3.3	0.099	66
$O_3{}^d$	3.6	0.074	97
N_2O	3.9	0.086	90
CO_2	4.3	0.245	35
O_3	4.75	0.166	57
H_2O	5.9	0.473	25
H_2O	6.5	0.534	24
CH_4	7.7	0.300	51
O_3	9.6	0.695	28

[a] mostly CO_2 with some water contribution; [b] mostly CH_4 with some water contribution; [c] mostly CO_2 with some water contribution [d] mostly O_3 with some N_2O contribution

dwarf stars, using the established approximation:

$$A_p = \frac{2R_p 5H}{{R_s}^2} \tag{2}$$

where A_p is the atmospheric contribution to the fractional transit depth, H is the pressure scale height, R_p is the planet radius and R_s is the stellar radius. Signals can also be found for specific spectral signatures, e.g. the 9.6 µm O_3 feature or the 2.7 µm CO_2 feature by measuring their amplitudes. We focus on M-dwarfs due to well-known the 'M-dwarf advantage' for detecting Earth-like planets.

4. Noise simulation

We use ExoSim [3], to calculate the noise on transit spectroscopy observations for different exosystems at different distances and for different instrument parameters, e.g. varying A_{tel}.

5. Deriving the yield

With the generic instrumental design established we are now examining the relationships between primary mirror size and SNR for detection of spectral features. These are used to derive an inner and outer distance limit for detectability (SNR > 5) for each instrument, for a given mission lifetime (e.g. 5 years). It is possible from this to establish a volume of detection, V_{det}, for each instrument, within which systems are detectable within the mission lifetime. Utilizing statistical information on the frequency of Earth-like planets, e.g. [4], and other parameters, the number of *potentially* detectable Earth-like atmospheres, n, can then be approximated by:

$$n = V_{det} \cdot \rho_M \cdot f_p \cdot \eta_e \cdot P_{tr} \cdot C \tag{3}$$

where ρ_M is the number density of M dwarfs in space, P_{tr} is the transit probability and C is a completeness factor that accounts for the fact that not all exosystems that exist will be known. Of these, a maximum fraction, f_{max}, can be observed within the mission lifetime. A maximum observed yield, n_{obs}, is thus given by:

$$n_{obs} = f_{max} \cdot n \tag{4}$$

This information will be key for optimal design of future missions that have the goal of establishing the frequency of life in the galaxy by obtaining a statistically significant number of spectra from Earth-like exoplanets.

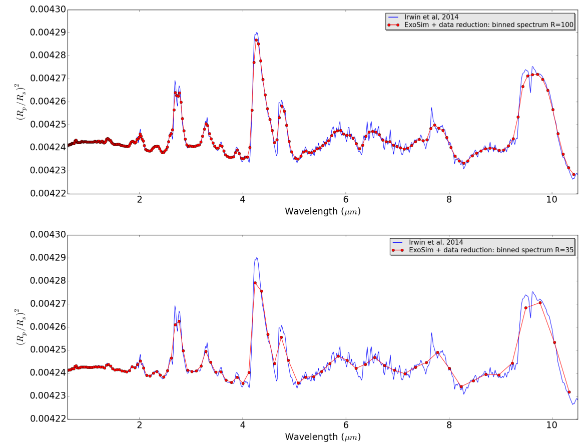

Figure 1: Model spectra (blue line) for an Earth-M dwarf primary transit generated by [2]. After passing through ExoSim's instrument model, producing noiseless light curves, R-binning and recovering the transit depth per spectral bin we obtain the binned data points (red dots). Top: R=100. Bottom: R=35.

References

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