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IMPACT OF CLOUDS ON REFLECTANCE SPECTRA OF EARTH-TWIN: DETECTABILITY OF OXYGEN A-BAND WITH LUVOIR TELESCOPE

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ABSTRACT

Over the next few decades, we will begin to characterize the atmospheres of terrestrial Earth-like planets with JWST, E-ELT, and future mission concepts like LUVOIR (Large UV/Optical/Infrared Surveyor). Also, clouds and hazes exist commonly in atmospheres of planets inside and outside of our solar system. While there are studies that address theoretical modeling of reflectance spectra of an Earth-twin considering the effect of clouds, the impact of cloud parameters (namely, the cloud coverage and the altitude of the cloud layer) has not been studied sufficiently. In this study, we examine these parameter impacts on reflectance spectra of Earth-twins at different geological epochs systematically. Especially, we focus on the oxygen A-band feature because oxygen can be considered as a most promising biosignature gas for terrestrial planets. As a result, we find that a cloud layer at low ($\lesssim$ 10 km) altitude can make the detection of the oxygen A-band easier while a cloud layer at high ($\gtrsim$ 10 km) altitude makes it more difficult compared to a clear sky atmosphere. We also simulate noises and calculate the integration time required to detect the oxygen A-band feature with test parameters for the future mission concept, LUVOIR. We find that a higher cloud coverage is preferred for a lower altitude cloud while lower cloud coverage is preferred for higher altitude cloud for its detection. The detection of the oxygen A-band with LUVOIR telescope will be possible with less than 100 hr integration time for an Earth-twin atmosphere with more than 0.1 PAL oxygen regardless of the cloud parameters. While it will be practicable for the atmosphere with 0.01 PAL oxygen as long as a high coverage ($\gtrsim$ 40%) cloud layer does not exist at high altitude ($\gtrsim$ 12 km).

Keywords: planets and satellites: terrestrial planets — planets and satellites: atmospheres — planets and satellites: detection

1. INTRODUCTION

Detection of more than 2900 exoplanets has been reported[1] thanks to recent advances in observational techniques. Among them, some are known to exist in habitable zones of their host stars (e.g., Kepler-62e and -62f; Borucki et al. (2013), Proxima b; Anglada-Escudé et al. (2016)). A next step would be the characterization of such potentially habitable planets. While the existence of molecular oxygen, O_2, in the atmosphere has been long considered as the most robust biosignature for Earth-like planets, several abiotic sources of O_2 have been proposed so far (Wordsworth & Pierrehumbert 2014; Luger & Barnes 2015; Gao et al. 2015; Harman et al. 2015). However, the simultaneous detection of large abundances of O_2 and a reducing gas species can be still considered as a robust biosignature because reduced gasses and oxygen react rapidly with each other, such a detection assures a large surface flux of O_2 (Rugheimer et al. 2013).

The amount of oxygen in the Earth's atmosphere has varied with its evolution with two distinct rises (Lyons et al.

[1] http://exoplanets.org, 2016 Oct 1

2014). The amount of oxygen in the atmosphere of Earth-like planets can be expected to also vary with the planet's evolution. Note that oxygen might not evolve at the same rate as the Earth. While it could be much less, it is likely not much more due to widespread fires if oxygen increases to 25 % - 30 % of the atmosphere (Lenton & Watson 2000).

Clouds and hazes seem to be commonly present in atmospheres of planets inside and outside our solar system. Cloud or hazes have been observed in the atmosphere of most of the planets and moons in our solar system with a variety of composition (see Morley et al. 2013, and references therein): H_2SO_4 cloud on Venus, H_2O and CO_2 clouds on Mars, NH_3 cloud on Jupiter, NH_3 and H_2O clouds on Saturn, CH_4 cloud and tholin haze on Titan, and CH_4-derived clouds and hazes on Uranus and Neptune. Also, clouds and hazes seem to exist in the atmosphere of exoplanets from their flat or featureless transmission spectra (Kreidberg et al. 2014; Sing et al. 2016). The existence of clouds can impact both the transmission and the reflectance spectrum. Due to the high albedo of clouds compared to that of the Earth's surface, clouds can deepen molecular absorption features but they can also obscure features lower in the atmosphere.

A suitable method of detection of habitable planets around F, G, and K type star is a reflectance spectrum due to their large separations from the host stars while a transmission spectrum is suitable for the detection of habitable planets around M type star because of the short orbital periods (large transit probability) and the large planet-to-star radius ratios. Aiming at further detection and characterization of exoplanets, some ground-based and space-based telescopes such as the James Webb Telescope (JWST) and E-ELT are being planned. Also, future mission concepts like LUVOIR (Large UV/Optical/Infrared Surveyor) has been proposed. Compared to JWST, the mission concept for LUVOIR will have a much larger diameter for its primary mirror (LUVOIR, > 8 m; JWST, ~ 6.5 m) and it will probe shorter wavelengths (LUVOIR, 0.1-1.8 μm; JWST, 0.6-28.5 μm). If equipped with a coronagraph or starshade, LUVOIR will be suitable for the detection and characterization of habitable planets around F, G, and K stars via reflectance spectrum while JWST is best suited suitable for transiting planets around M dwarfs.

Rugheimer et al. (2013) modeled reflectance spectra of Earth-like planets orbiting around F, G, and K stars considering the existence of clouds in the atmospheres and probed the impact of stellar types and UV levels to provide a framework for future observations of atmospheres of habitable Earth-like planets. However, they only considered Earth-analog clouds with modern O_2 concentrations. In this study, we examine the impacts of variations in cloud properties (i.e., the cloud coverage and the altitude of the cloud layer) and the amount of oxygen through the evolution of the planet on reflectance spectra of an Earth-twin, especially focusing on the oxygen A-band (0.76 μm) feature, which is the most prominent absorption feature of oxygen in the optical and near-infrared wavelength. We also calculate noise and signal-to-noise ratio (SNR) of spectra to explore the detectability of the oxygen A-band feature with LUVOIR telescope.

The rest of this paper is organized as follows. In section 2, we describe our model. In section 3, we show the results of reflectance spectra of an Earth-twin and examine the impact of variations in cloud properties and the amount of oxygen on reflectance spectra. In section 4, we report the detectability of the oxygen A-band feature. In section 5 and 6, we discuss our model and summarize this paper.

2. METHODS

To calculate reflectance spectra of an Earth-twin, we use the existing model, Exo-P, developed for terrestrial planets and described in Kaltenegger & Sasselov (2010). This model comprises 3 models; a 1D climate model (Kasting & Ackerman 1986; Pavlov et al. 2000; Haqq-Misra et al. 2008), a 1D photochemistry code (Pavlov & Kasting 2002; Segura et al. 2005, 2007), and a line-by-line radiative transfer model (Traub & Stier 1976; Kaltenegger & Traub 2009).

We consider four cases of oxygen amount in the atmosphere; 0.01 PAL (2.0 Ga), 0.1 PAL (0.8 Ga; the rise of oxygen in the Earth's atmosphere), 0.5 PAL, and 1.0 PAL (modern Earth), where PAL stands for the present atmospheric level. In our calculation of Earth-twin's reflectance spectra, we assume a characteristic planet phase angle α as $\alpha = \pi/2 = 90^\circ$ (i.e., quadrature). We assume 70% of the planetary surface as ocean, 2% as coast, and 28% as land, whose surface consists of 30% grass, 30% trees, 9% granite, 9% basalt, 15% snow, and 7% sand for simulations of Earth-twin atmospheres with 0.5 PAL and 1.0 PAL oxygen. The land surface is assumed to consist of 35% basalt, 40% granite, 15% snow, and 10% sand for simulations of Earth-twin atmospheres with 0.01 PAL and 0.1 PAL oxygen. As for clouds, they are assumed to be cumulus clouds, which are present in the lower atmosphere of the Earth. Reflectivity data for surface compositions and clouds are taken from the USGS Digital Spectral Library[2] and the ASTER Spectral Library[3]. We assume that the cloud layer to be completely reflective surface. For the spectra of the Sun at different

[2] http://speclab.cr.usgs.gov/spectral-lib.html

[3] http://speclib.jpl.nasa.gov

epochs, we use the calculated spectrum models at 2.0 Ga, 0.8 Ga, and present time derived with a solar evolution model from Claire et al. (2012). Note that for the simulation of Earth-twin atmospheres with 0.5 PAL oxygen, we use the modern Sun's spectrum.

For the noise calculation, we use the model which Robinson et al. (2016) originally developed for WFIRST-AFTA. We have modified this noise calculator to match projected LUVOIR values. Parameters we use are listed in Table 1.

Table 1. Values of the parameters used

Symbol	Description	Value
D	Telescope diameter	10 m
R	Instrument spectral resolution	140
T_{eff}	Stellar effective temperature	5777 K
R_s	Stellar radius	1 R_{sun}
d	Distance to observed star-planet system	5 pc
R_p	Planetary radius	1 R_{earth}
a	Semi-major axis	1 AU

3. REFLECTANCE SPECTRA

Figure 1 shows the reflective spectrum models of a clear sky and 100% coverage cloud layer at 1.7 km atmosphere. Various molecular absorption features, especially, a strong absorption feature coming from the oxygen A-band at 0.76 μm, can be seen in these spectra (e.g., an ozone absorption feature at 0.76 μm, a water absorption feature at 0.9 μm, and a methane absorption feature at 1.7 μm). It is realized that cloud makes the flux larger because of its high albedo.

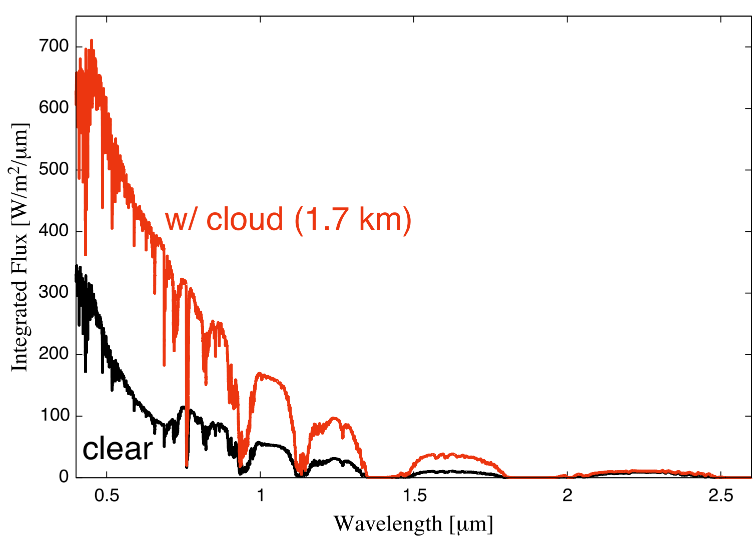


Figure 1. Reflective spectrum models of a clear sky atmosphere (black line) and the atmosphere with 100% coverage cloud layer at 1.7 km atmosphere (red line).

Spectrum models for the atmosphere with cloud layer of different altitudes are shown in Figure 2. The lower the altitude of the cloud is, the larger the flux at the continuum becomes. This behavior is due to the Rayleigh scattering of gaseous species in the atmosphere. Also, the lower the altitude of the cloud is, the deeper the molecular features is. This is just because the optical depth is larger at the lower altitude.

Figure 3 (a) shows the spectrum models only around the wavelength of the oxygen A-band feature. Flux at peak is smaller for the lower cloud while flux at the continuum is larger for the lower cloud. This is because of the Rayleigh scattering of gaseous species in the atmosphere. And the models are plotted in relative absorption in Figure 3 (b).

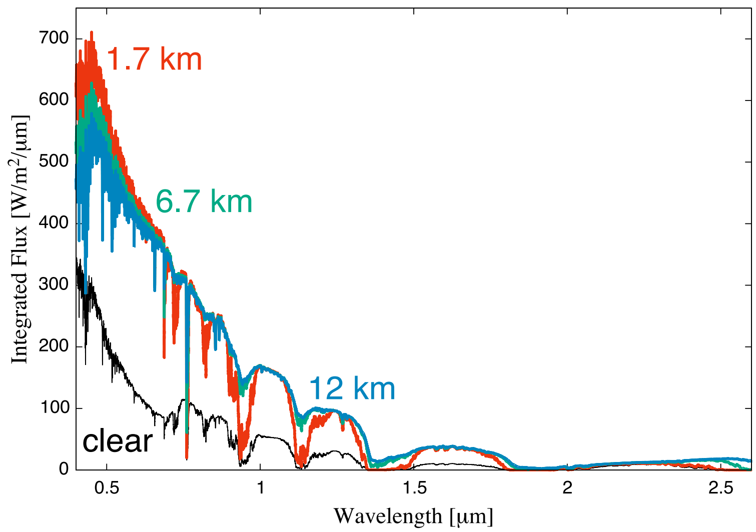
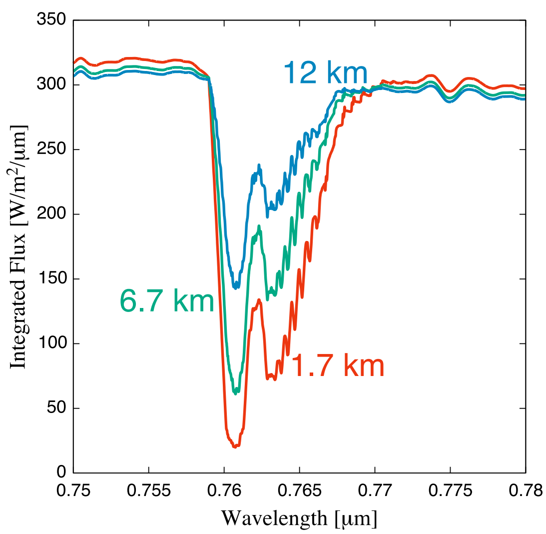
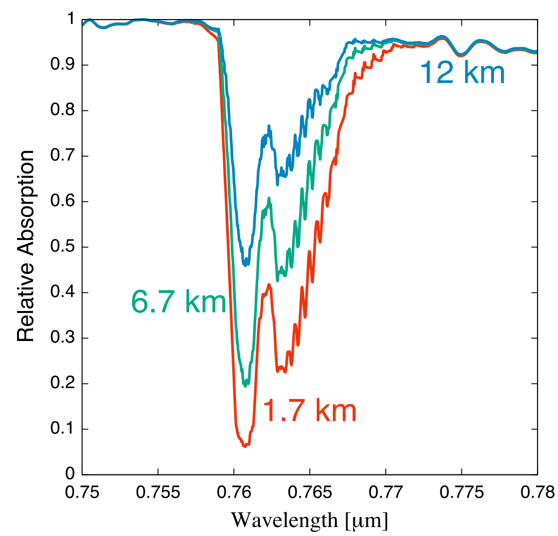


Figure 2. Reflective spectrum models for three different cloud altitude of 1.7 km (red line), 6.7 km (green line), and 12 km (blue line) are shown. 100% cloud coverage is assumed for all these models. Spectrum model of a clear sky atmosphere is also plotted with black line.

For the lower cloud, the relative absorption of the oxygen feature is deeper.



(a) Integrated Flux



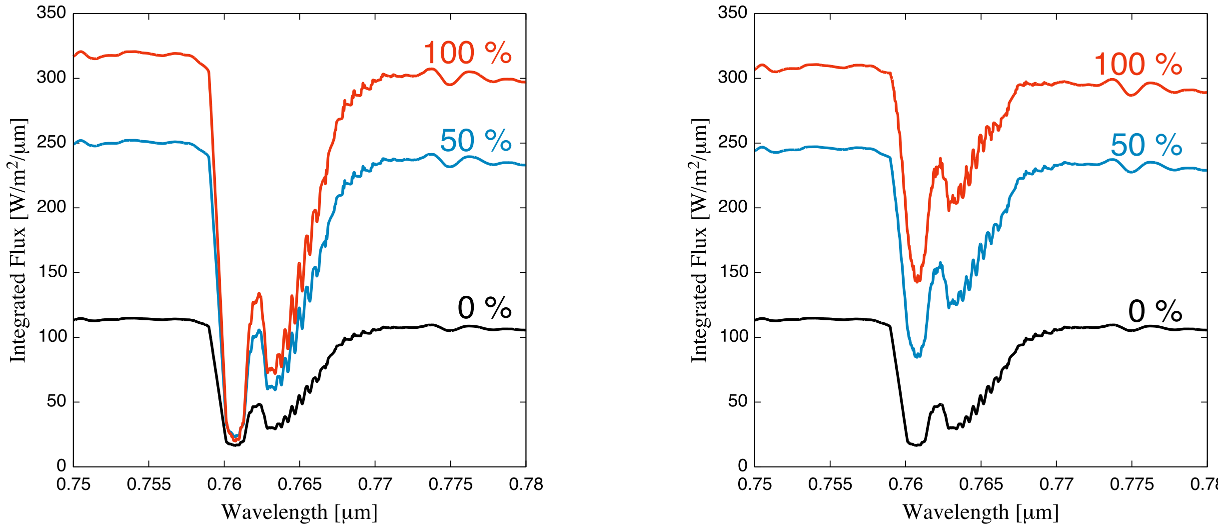
(b) Relative Absorption

Figure 3. Same as Figure 2, but only around the wavelength of oxygen A-band is shown. Models are plotted in (a) integrated flux and (b) relative absorption, respectively.

Next, we discuss the dependence of the cloud coverage. In Figure 4, the left panel shows the reflectance spectrum models for 1.7 km cloud while the left one shows those for 11 km cloud. As for the right panel, the flux at the peak does not vary as the atmosphere at 1.7 km is optically thick enough while the flux at the peak varies for 11 km cloud case because the atmosphere at 11 km is optically thin. Also, you can see that the cloud's high albedo makes the continuum increase when the cloud coverage is increased.

Figure 5 are same as before, but the vertical axes show relative absorption. It can be seen that for 2 km case, the relative absorption does not vary much with the cloud coverage. On the other hand, the relative absorption varies with the cloud coverage for 13 km case.

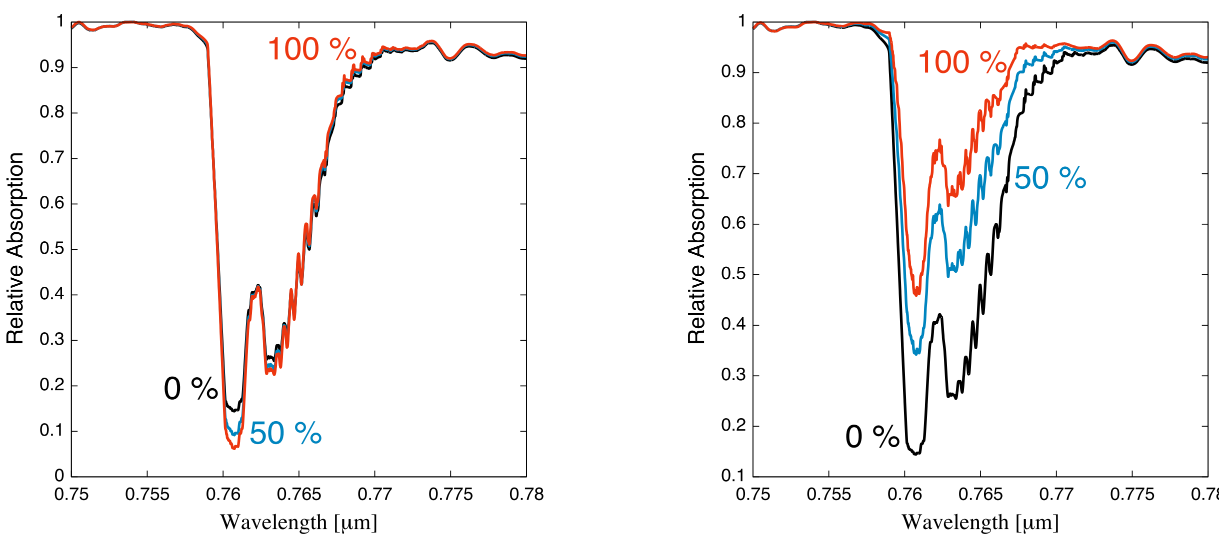
Figure 6 shows the change of the oxygen A-band feature with the evolution of the planet. Note the depth of the feature does not vary linearly with the amount of oxygen.



(a) 1.7 km cloud layer

(b) 11 km cloud layer

Figure 4. Reflective spectrum models for three different cloud coverage of 0% (black line), 50% (blue line), 100% (red line). The altitudes of cloud layer assumed are (a) 1.7 km and (b) 11 km, respectively.



(a) 1.7 km cloud layer

(b) 11 km cloud layer

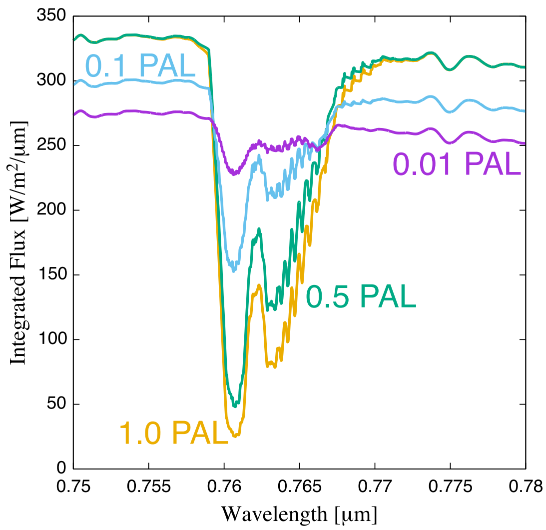
Figure 5. Same as Figure 4, but the models are plotted in relative absorption.

4. DETECTABILITY

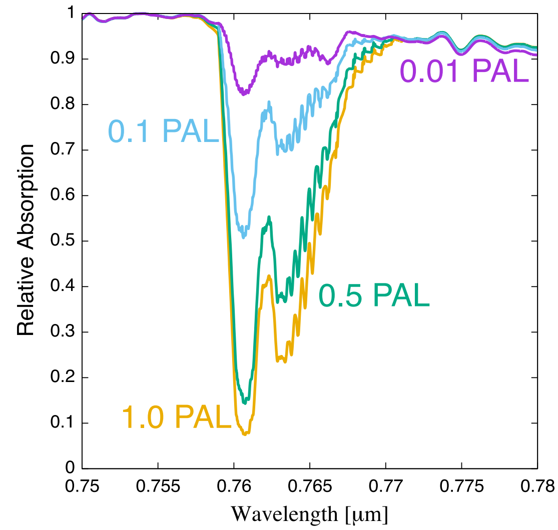
Figure 7 shows the result of the spectra models with noise for the clear atmosphere and the atmosphere with the cloud layer of 1.7 km altitude and 60% cloud coverage. We use the SNR value of 5.

The spectra with cloud layer of different altitudes and with noises only around the wavelength of the oxygen A-band are shown in Figure 8. The integration time required to detect the feature with LUVOIR telescope is 0.28 hr, 0.55hr, 1.2 hr for 1.7 km, 6.7 km, and 12 km cloud layer, respectively. 60% cloud coverage is assumed for all these models. Note that it would take 17.5 hr to detect an ozone feature at 0.6 μm in the atmosphere of an Earth-twin at 10 pc with a 6.5 m space-based telescope like JWST, which we derive from the results of Kaltenegger & Traub (2009) assuming SNR = 5.

Figure 9 shows the integration time required to detect the oxygen A-band feature shown with the color counter for different Earth-twin's epoch. Some key cases are tabulated in Table 2-5. The trend we have mentioned in Figure 4 can be seen; As for the higher altitude cloud, a lower cloud coverage makes the feature deeper and the detection easier



(a) Integrated Flux



(b) Relative Absorption

Figure 6. Reflective spectrum models for four geological epoch are shown. The amounts of oxygen are 0.01 PAL (purple line), 0.1 PAL (light blue line), 0.5 PAL (green line), and 1.0 PAL (orange line), respectively. Models are plotted in (a) Integrated Flux and (b) Relative Absorption, respectively. 2.0 km cloud layer altitude and 60% cloud coverage are assumed for all the models.

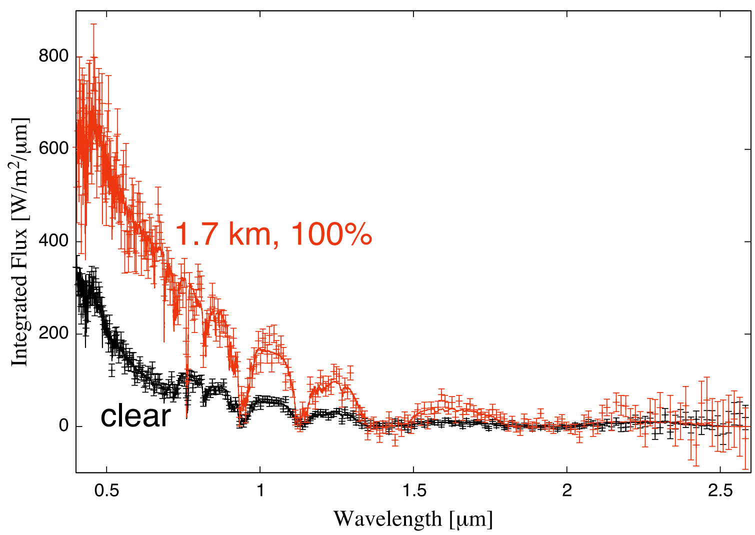


Figure 7. Same as Figure 1, but noise models with SNR = 5 are also plotted.

while a high cloud coverage deepens the features and makes the detection easier for the lower altitude cloud. From these results, we can conclude that the oxygen A-band with LUVOIR telescope will be detectable with less than 100 hr integration time for an Earth-twin atmosphere with more than 0.1 PAL oxygen regardless of the cloud parameters. While its detection will be practicable for the atmosphere with 0.01 PAL oxygen as long as a high coverage ($\gtrsim$ 40%) cloud layer does not exist at high altitude ($\gtrsim$ 12 km).

5. DISCUSSION

In this study, we have probed the impact of the cloud parameters (i.e., the cloud coverage and the altitude of the cloud layer) on reflectance spectra of an Earth-twin. However, their values do not have physical-basis. The distribution and the size of the cloud particles should be derived from a microphysical cloud model such as Zsom et al. (2012), which we will do when we publish this paper. As the motivation of this work is to explore the influence of the cloud parameters systematically, this is beyond the scope of this study. Also, in our calculation, the cloud layer is assumed

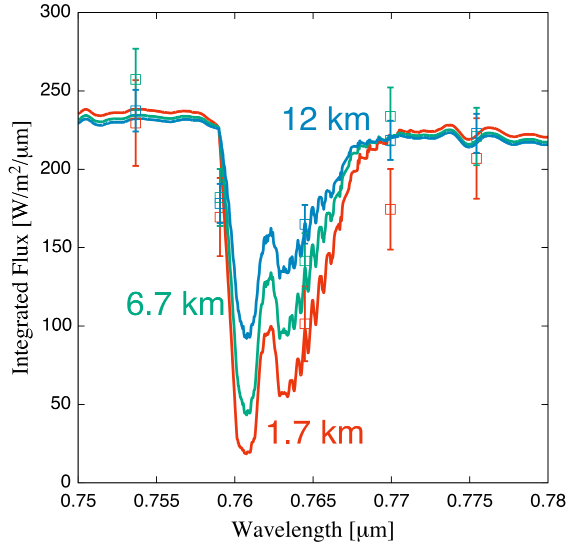


Figure 8. Reflective spectrum models with noise models for three different cloud altitude of 1.7 km (red line), 6.7 km (green line), and 12 km (blue line) are shown. 60% cloud coverage is assumed for all these models.

Table 2. Integration time required to detect oxygen A-band feature: 0.01 PAL

	Cloud coverage			
Altitude of Cloud Layer	0 %	40 %	60 %	100 %
18 km	194 hr	374 hr	541 hr	1340 hr
11 km		221 hr	233 hr	257 hr
1.7 km		47.7 hr	31.8 hr	17.9 hr

Table 3. Integration time required to detect oxygen A-band feature: 0.1 PAL

	Cloud coverage			
Altitude of Cloud Layer	0 %	40 %	60 %	100 %
18 km	16.7 hr	28.8 hr	38.7 hr	75.9 hr
11 km		15.3 hr	14.7 hr	13.7 hr
1.7 km		3.62 hr	2.36 hr	1.29 hr

Table 4. Integration time required to detect oxygen A-band feature: 0.5 PAL

	Cloud coverage			
Altitude of Cloud Layer	0 %	40 %	60 %	100 %
18 km	1.61 hr	3.40 hr	5.33 hr	18.6 hr
11 km		1.84 hr	1.96 hr	2.20 hr
1.7 km		0.611 hr	0.440 hr	0.268 hr

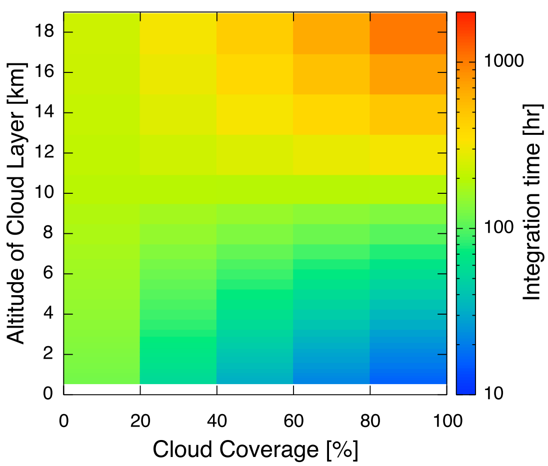
to be completely reflective surface. In reality, however, some light can penetrate the cloud layer depending on the thickness and the denseness of the cloud layer and the particle size of the cloud particles. This effect cannot be studied without deriving the distribution and the size of the cloud particles.

6. SUMMARY AND CONCLUSIONS

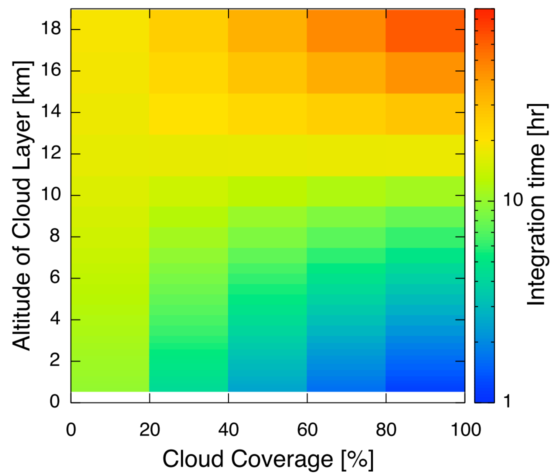
We have examined the impact of the clouds on reflectance spectra of an Earth-twin at different geological epochs systematically. We focused on the oxygen A-band feature because oxygen can be considered as a most promising

Table 5. Integration time required to detect oxygen A-band feature: 1.0 PAL

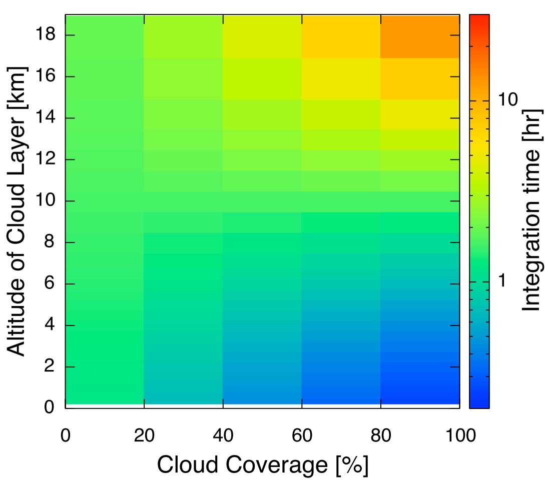
Altitude of Cloud Layer	Cloud coverage 0 %	40 %	60 %	100 %
18 km		2.14 hr	3.18 hr	8.93 hr
11 km	1.09 hr	1.10 hr	1.10 hr	1.11 hr
1.7 km		0.397 hr	0.284 hr	0.171 hr



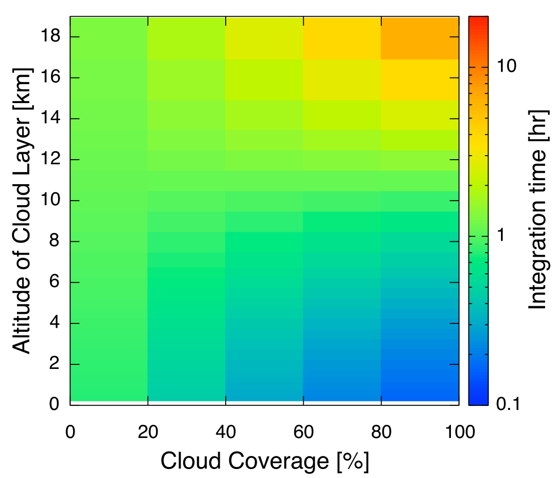
(a) 0.01 PAL (2.0 Ga)



(b) 0.1 PAL (0.8 Ga)



(c) 0.5 PAL



(d) 1.0 PAL (modern Earth)

Figure 9. Integration time required to detect oxygen A-band feature for four different amount of oxygen; 0.01 PAL (2.0 Ga), 0.1 PAL (0.8 Ga), 0.5 PAL, and 1.0 PAL (modern Earth).

biosignature gas for terrestrial planets. As a result, we find that some cloud parameters can make the detection of the oxygen A-band easier while other parameters can make it more difficult to detect compared to a clear sky atmosphere. We have also simulated noises and calculate the integration time required to detect the oxygen A-band feature with the future mission concept, LUVOIR. We find that a higher cloud coverage is preferred for the lower altitude cloud while a lower cloud coverage is preferred for the higher altitude cloud for its detection. The detection of the oxygen A-band with LUVOIR telescope will be possible with less than 100 hr integration time for an Earth-twin atmosphere with more than 0.1 PAL oxygen regardless of cloud parameters. While it will be practicable for the atmosphere with 0.01 PAL oxygen as long as a high coverage ($\gtrsim 40\%$) cloud layer does not exist at high altitude ($\gtrsim 12$ km).

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