CHARACTERIZING EARTH-LIKE PLANETS USING A COMBINATION OF HIGH-DISPERSION SPECTROSCOPY AND HIGH-CONTRAST INSTRUMENTS:
DOPPLER-SHIFTED WATER AND OXYGEN LINES

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ABSTRACT

Future radial velocity, astrometric and direct imaging surveys will find nearby Earth-sized planets within the habitable zone (HZ) in the near future. How can we search for water and oxygen in those non-transiting planets? We propose a combination of high-dispersion spectroscopy and coronagraphic techniques as a method to detect molecular lines in Earth-like planets (ELPs). In this method, the planetary signals are spectrally resolved from the telluric absorption due to the Doppler shift. Assuming a long observing campaign (T_{exp} = 20 days) using the high-dispersion spectrometer (R = 50,000) with the speckle suppression on a 30 m telescope, we simulate the spectra from the ELPs around M dwarfs at 5 pc. Performing the cross-correlation analysis with the binary template of the molecular lines, we find that the raw contrasts of 10^{-5} (0.8-1.8 μm) and 10^{-4.5} (use of J-band only) at 30 mas are required to detect the water vapor for a ∼ 4 – 5σ detection. The raw contrast of 10^{-5} is required for a 4 σ detection of the oxygen 1.27 μm band. For the ELPs around solar-type stars, it is necessary to assume a several hundred times better contrast than that for M dwarfs in order to detect water vapor. This method does not require any additional post-processings and is less sensitive to the terrestrial noise than the low resolution spectroscopy. We conclude that a combination of high-dispersion spectroscopy and high-contrast instruments can be a powerful means to characterize the ELPs in the extremely large telescope era.

Subject headings: astrobiology – techniques: spectroscopic – planets and satellites: atmospheres – methods: observational

1. INTRODUCTION

The spectroscopic detection of the atmospheric water vapor, oxygen and other biosignatures will be the first step to search for exolife in exoplanets. Direct imaging from space has been regarded as a promising way to find the Earth-like planets (ELPs) in the habitable zone (HZ). In this case, low resolution spectroscopy (typically the resolving power R ∼ 100 – 1000) will be a means of searching for the water vapor and other biosignatures (e.g. Des Marais et al. 2002; Turnbull et al. 2006; Kaltenegger et al. 2007). The strong molecular features including a lot of water bands, the oxygen 760 μm band, and the ozone 10 μm band are the targets of the biosignatures search for the proposed dedicated space missions.

The low resolution spectroscopy of the direct imaging with extremely large telescopes (ELTs) has also been considered in the context of the search for oxygen in the ELPs around the late-type star (Kawahara et al. 2014) because the contrast of the habitable planets around a M-type star is ∼ 100 times easier than those around G-type stars (e.g. Matsuo & Tamura 2010; Kawahara et al. 2012; Guyon et al. 2012; Crossfield 2013; Males et al. 2014). However, the sophisticated post-processing is required to reach the typical planet-star contrast of ∼ 10^{-8} from the raw contrast of 10^{-4} – 10^{-5} for Earth-sized planets in the HZ. The accurate calibrations of the time-variable night airglow spectrum and the telluric transmittance are also crucial for the low-resolution spectroscopy (Kawahara et al. 2012). Furthermore, the molecular detection with the low resolution spectroscopy requires the full spectrum modelling of the planets because many thin lines are blended in the spectrum.

In principle, the high-dispersion spectroscopy can solve those problems. Simultaneous identification of plenty of rotational-vibrational molecular lines makes the detection of the molecule robust. In solar system, Spinrad et al. (1963) firstly reported the detection of Martian water vapor using the Mount Wilson 100-inch reflector in the near infrared (NIR) band. Performing a high-dispersion observation, they could separate the Martian water lines with the Doppler-shift ∆V = 15 km/s from the telluric lines. To date, the Doppler-shifted water lines in hot Jupiters have been detected despite the weak signal with the planet-star contrast below 10^{-3} (Birkby et al. 2013; Lockwood et al. 2014; Brogi et al. 2014). Snellen et al. (2013) proposed to use the high-dispersion transmission spectroscopy to detect the oxygen 760 μm lines for the transiting ELPs around nearby late-type stars. Rodler & López-Morales (2014) further studied its feasibility and concluded that the detection will be feasible with the ELTs for an Earth-analog within 8 pc, in the most optimistic cases. As demonstrated by them, the high-dispersion transmission spectroscopy is a promising means to characterize the transiting ELPs.

Recent progress of the radial velocity (RV) survey has significantly improved the RV precision. There have been a number of planned RV instruments for the nearby planet survey (e.g. CARMENES, CRIRES-ESPRESSO, HPF, IRD, SPITRON; Quirrenbach et al. 2010; Pepe et al. 2010; Kotani et al. 2013; Artigau et al. 2014). The RV precision ∼ 1 m/s in the NIR covers an Earth-sized planet around nearby late-type stars. The unprecedented precision 10 cm/s in the visible band of
the requirement of ESPRESSO, reaches rocky planets around the solar-type stars (Pepe et al. 2010). After the discovery of those planets in near future, how can we characterize nearby habitable planet candidates to search for the exolife? It is important to explore the characterization methods applicable to the non-transiting ELPs. For the non-transiting planet, the first detection of the Doppler shifted molecular lines was achieved by Snellen et al. (2014). They performed the high-dispersion slit spectroscopy of the self-luminous direct-imaged planet, b Pictorias b and detected the Doppler-shifted carbon monoxide lines at the position of the planet. Using the adaptive optics, they could obtain a 9-30 times better contrast at the planet than that in the integrated light. A combination of the high-contrast instrument and the high-dispersion spectroscopy will be one of promising ways for characterization of exoplanets (see also Kawahara et al. 2014; Brandl et al. 2014).

In this paper, we consider the high-dispersion spectroscopic detection of water vapor and oxygen in the ELPs (earth-analog) within the HZ, assuming using future high-contrast and high-dispersion instruments on the ELTs. We also consider the stellar lines scattered by the ELP.

The paper is organized as follows. In Section 2, we explain the concept of the doppler-shifted water, oxygen and the scattered stellar lines and describe the statistics for a given planetary system and instrumental and observational conditions. In §3, the spectra at the planet position are created including the planetary scattered spectrum simulated by the radiative transfer code, the stellar speckle, the night airglow, and the terrestrial transmission. The cross correlation analysis of the mock spectra and the binary template of the molecular lines is performed to study the feasibility. We also investigate the sensitivity of the results to the systematics. In §4, we summarize our results.

2. HIGH-DISPERSION OBSERVATION OF EARTH LIKE PLANETS WITH GROUND-BASED TELESCOPES

In this section, we explain what type of observation we assume and show how this method works using orders of magnitude arguments. We consider the high-dispersion spectroscopy of the ELPS after the speckle suppression using the high-contrast instruments. The planetary signals are spectroscopically separated from the stellar speckle and the terrestrial lines. We assume an observing campaign of one planet with the long exposure time (≈ 20 days) because the RV or other planet surveys will have detected the target planet in the HZ in the near future.

We also assume that the aperture extracted for the spectrum analysis is fixed at the planet position. If the planet can be detected by the astrometric observation or the direct imaging with the post-processing and, as a result, the position angle of the planet is known, one can perform a slit spectroscopy or a fiber spectroscopy at the planet position. If we do not utilize the astrometric observation nor the direct imaging, this type of observation requires integral field spectroscopy with the high spectral resolution because we only know the angular separation of the planet and the host star in this case. However, we consider no more about the detector-type and concentrate on the signals at the planetary position.

2.1. Classification of the Molecular Lines

To separate the planetary signals, we utilize the relative velocities of the star, the planet, and the observer frame. The origins of the molecular lines in the integrated spectrum are characterized by the relative velocity as shown in Table 1. The Doppler-shifted molecular lines originating from the planetary atmosphere (the planetary lines) have the relative velocity of the sum of the velocity due to the orbital motion of the planet $V_p$ and the peculiar velocity of the system $V_{sys}$ to the observer (the relative velocity between the star and the Sun and the orbital and spin motion of the Earth). The lines originating from the stellar spectrum are imprinted in the integrated spectrum in two ways with different Doppler velocities. One is imprinted in the planetary spectrum because the scattered light of the planet is originally the star light. Those lines are regarded as the planetary signals as well as the planetary lines with the peculiar velocity, $v = V_{sys} + V_p$. We refer to those lines as the scattered stellar lines. The other is simply from the speckle, i.e. the contamination of the central starlight (the speckle stellar lines), which has the peculiar velocity of the system $v = V_{sys}$. Hence this velocity difference between the direct star light and the scattered star light is $V_p$. The scattered stellar lines have been proposed as a tracer of scattered lights of exoplanets by Martins et al. (2013). Finally, the telluric water vapor, oxygen and other species make a lot of absorption lines in the spectrum and OH and $O_2$ emit peculiar lines, i.e. the night airglow. Those lines have velocity of the observer frame, i.e. $v = 0$ in our definition. We refer to those lines as the telluric lines.

The radial velocity due to the planetary orbital motion is expressed as

$$V_p = v_{\text{orb}} \sin i \sin(\omega t),$$

for a circular orbit, where $v_{\text{orb}}$ indicates the orbital velocity of the planet, $i$ is the orbital inclination, and $\omega$ is the orbital angular velocity. The typical orbital velocity at the HZ (Kopparapu et al. 2013) around the main sequence stars is 20-50 km/s for the stellar mass $M_*=0.1-1M_\odot$. The orbital velocity at the HZ generally increases as the stellar mass decreases. Hence, the high resolution spectroscopy with $R \sim 10^5$ can distinguish the velocity difference $V_p$ unless the system is almost face-on ($i \lesssim 20-30^\circ$).

| Classification of molecular lines in the integrated light |
|------------------------------------------------------------|
| lines     | velocity | origin                  |
|-----------|----------|-------------------------|
| Planetary lines | $V_p + V_{sys}$ | $A(\lambda)$ in $f_p(\lambda)$ |
| Scattered stellar lines | $V_p + V_{sys}$ | $F_*(\lambda)$ in $f_p(\lambda)$ |
| Speckle stellar lines | $V_{sys}$ | $f_{\text{speckle}}(\lambda)$ |
| Telluric lines | 0 | $T(\lambda)$ |
| Airglow | 0 | $f_{\text{sky}}(\lambda)$ |

The spectrum at the planet position is modeled as

$$f_{\text{tot}}(\lambda) = T(\lambda)f_p(\lambda) + f_{\text{speckle}}(\lambda) + f_{\text{sky}}(\lambda) + f_n(\lambda),$$

where $T(\lambda)$ is the terrestrial transmittance, $f_p(\lambda)$ and $f_{\text{speckle}}(\lambda)$ indicate the Doppler shifted planetary and
spatial noise. The night airglow and the instrumental noise, such as the readout noise, are denoted by $f_{\text{sky}}(\lambda)$ and $f_n(\lambda)$. Let us explain each term in detail below.

The planetary spectrum is shifted as

$$f_p(\lambda) \Delta \lambda \equiv f_{\text{raw}}(\lambda) T(\lambda) F_\star(\lambda \delta') \frac{\Delta \lambda}{\delta'},$$

where $f_p(\lambda)$ is the rest-frame planetary spectrum. One of the dominant noises is the speckle noise from the stellar light, in other words, the contamination of the stellar light at the position on the detector. This leakage from the stellar light is expressed as

$$f_{\text{speckle}}(\lambda) \Delta \lambda \equiv C_{\text{raw}}(\lambda) T(\lambda) F_\star(\lambda \delta') \frac{\Delta \lambda}{\delta'},$$

where $C_{\text{raw}}(\lambda)$ is the raw contrast with the point spread function (PSF) circle at the planet position and $F_\star(\lambda)$ is the rest-frame stellar spectrum. In this paper, we assume a constant value of the raw contrast, $C_{\text{raw}}(\lambda) = C_{\text{raw}}$.

2. Estimating the Required Flux and the Speckle Suppression to Detect Molecular Lines

The total luminosity of the scattered light of an Earth-sized planet in the HZ does not depend much on the stellar type because the incoming energy required to maintain habitability is approximately constant and the scattered light is part of its incoming energy. An Earth-analog with $R_\oplus$ and $A=0.3$ has magnitudes of 27-29 in the NIR (I, J and H) band at distances $d = 5$ and 10 pc. Table 2 provides the typical magnitude of the expected scattered light of an Earth analog at $d = 5$ and 10 pc around M-type and G-type stars.

| $T_\star$ | a | d | I | J | H | $C_{\text{ps}}$ |
|----------|---|---|---|---|---|-----------|
| #M 3500 K | 0.15 au 5 pc 27 26 26 | 5 $\times$ 10$^{-9}$ |
| #G 5750 K | 1 au 10 pc 29 29 28 | 1 $\times$ 10$^{-10}$ |

Table 2: Typical Magnitude and Contrast of an Earth Analog at the HZ

The number of photons in $\Delta \lambda$ (the width of the spectrum) for $R = 10^5$ is expressed as

$$n_p \Delta \lambda \approx 10^3 \left( \frac{F}{F_{-19}} \right) \left( \frac{\eta}{0.1} \right) \left( \frac{T_{\text{exp}}}{20 \text{ days}} \right) \left( \frac{D}{30 \text{ m}} \right)^2 \left( \frac{R}{10^5} \right)^{-1} [\text{cts/bin}],$$

where $F_{-19} = 10^{-19} [\text{erg/s/cm}^2/\text{nm}]$, corresponding to $J = 26.3$ and $\eta$ is the instrumental total throughput. We adopted $\eta = 10\%$ for the high-dispersion instrument and a 20-day exposure time.

To what extent each molecular line contributes to the detection of planetary molecules as

$$(S/N)_{\text{det}} \approx r \sqrt{N_{\text{eff}}(S/N)_{\text{spectra}}},$$

where $r$ is the ratio of the planetary flux and the total flux in the aperture,

$$r = \frac{n_p}{C_{\text{raw}} n_\star + n_p + S_{\text{sky}} \Delta \Omega},$$

where $n_\star$ is the stellar flux in photon counts, $C_{\text{raw}} n_\star$ is the photon count of the speckle noise within the aperture $\Delta \Omega$ and $S_{\text{sky}}$ is the sky surface brightness due to the night airglow. The raw contrast of the high-contrast instruments is denoted by $C_{\text{raw}}$, which is defined by the ratio of total photon count of an on-axis source and the photon count within the PSF circle at the planet position. We assume that the aperture has the size of the PSF. In this case, the definition of $C_{\text{raw}}$ provides a similar value of the PSF (raw) contrast defined by Guyon (2005). The raw contrast $C_{\text{raw}}$ is generally worse than the final contrast for the direct imaging after PSF subtractions such as ADI, SSDI and TLOCI.

If the noise is dominated by the speckle, equation (6) yields

$$(S/N)_{\text{det}} \approx \frac{C_{\text{ps}}}{C_{\text{raw}}} \sqrt{N_{\text{eff}}(S/N)_{\text{spectra}}} \sqrt{N_{\text{eff}} n_p \Delta \lambda},$$

where $C_{\text{ps}} \equiv F_p / F_\star$ is the planet-star contrast.

For the scattered light, the planetary flux is expressed as

$$F_p(\lambda) = \frac{2}{3} \phi(\beta) \left( \frac{R_p}{a} \right)^2 A(\lambda) F_\star(\lambda),$$

where $R_p$ is the planet radius, $\phi(\beta)$ is the phase function as a function of the observer-star-planet angle $\beta$, and $A(\lambda)$ is the spherical albedo (Sobolev 1975). On the isotropic assumption, one can obtain $\phi(\beta) = [\sin \beta + (\pi - \beta)] \cos \beta / \pi$.

Then,

$$C_{\text{ps}} = \frac{2}{3} \phi(\beta) \left( \frac{R_p}{a} \right)^2 A(\lambda),$$

3 In Guyon (2005), the PSF contrast is defined by the ratio of the intensity at the point of the target, $I(\theta)$ and the intensity at the PSF center, $I(0)$, i.e., $C_{\text{PSF}} \equiv I(\theta)/I(0)$. Using these notations, our definition of $C_{\text{raw}}$ can be written as $C_{\text{raw}} = \int_{\Delta \Omega} d \Omega' I(\theta' - \theta) \int d \Omega I(\theta')$. Assuming that $\Delta \Omega$ is the PSF size, $\int_{\Delta \Omega} d \Omega' I(\theta' - \theta) \approx I(\theta) \Delta \Omega$ and $\int d \Omega I(\theta') \approx I(0) \Delta \Omega$. Then, we obtain $C_{\text{raw}} \approx C_{\text{PSF}}$. 

2 Strictly speaking, the incoming stellar spectrum to the planet slightly differs from the stellar spectrum we observe (i.e., it affects the shape of the speckles) because the relative rotation velocity between the stellar spin and the orbital motion of the planet broadens the scattered spectrum. We ignore this difference and regard them as the same spectra in our simulation because the relative rotation velocity is the same order of the stellar rotation or smaller for our case. We note that one cannot ignore this effect for very close-in planets with several days of the period. In this paper, we do not consider the slight shift of the planet radial velocity due to the spin rotation neither, which can be used to determine the planetary obliquity (Kawahara 2012).
where $A(\lambda)$ is the wavelength average of the spherical albedo. Assuming an Earth-sized planets with $A(\lambda) = 0.3$, we obtain $C_{ps} \sim 5 \times 10^{-5}$ at $a = 0.15$ au for the inner edge of the HZ around early M-type stars and $C_{ps} \sim 10^{-10}$ at $a = 1$ au for the inner edge of the HZ around G-type stars.

For the 5-sigma detection of the signal, we obtain

$$C_{raw} < \frac{1}{\sqrt{2}} N_{eff}(n_p \Delta \lambda) C_{ps}. \tag{11}$$

Hence, the $C_{raw}$ required to detect the signal is estimated as, for instance, $C_{raw} \sim 10^{-4} - 10^{-5}$ for $C_{ps} = 5 \times 10^{-9}$ (M-type) or $C_{raw} \sim 10^{-6} - 10^{-7}$ for $C_{ps} = 10^{-10}$ (G-type) if $N_{eff}$ is hundreds and $n_p \Delta \lambda$ is hundreds cts per bin. From those simple estimates, we find that the requirements of the raw contrast are $C_{raw} \lesssim 10^{-4}$ for M-type stars and $C_{raw} \lesssim 10^{-6}$ for G-type stars. Are these assumptions feasible in the ELT-era? This is actually an actively developing field and estimating the feasibility is difficult. Korkiakoski & Verinaud (2010) simulated the performance of the ExAO for EPICS. Their results show the raw contrast is $C_{raw} \sim 10^{-5}$ at 30 mas (the HZ for M-type stars) and $C_{raw} \sim 10^{-6}$ at 100 mas (the HZ for G-type stars).

Guvon et al (2012) considered the direct imaging of the rocky planets around M dwarfs using ELTs. They presented the PSF raw contrast for a target with $I$ magnitude=8.5 assuming the wavefront sensing in I-band. They showed that the expected PSF raw contrast in H-band should be below $10^{-5}$ for angular separation $\theta > 5 - 25$ mas, depending on the sampling frequency (Figure 8 in their paper). Hence, the assumption of $C_{raw} \sim 10^{-4} - 10^{-5}$ at 30 mas is feasible in the ELT era. The raw contrast $10^{-6} - 10^{-7}$ at 100 mas for G-type stars is clearly more difficult than that for M-type stars. Though we could not find any relevant references to reach these contrast, we also consider the case of G-type stars for future significant improvement of the ExAO.

Because the uncertainty of $N_{eff}$ remains in those estimates, depending on the depth of lines, the contamination of the neighbor lines, and the number of lines that survive against the terrestrial absorption, we need the detailed simulations as presented in the next section. The strong water lines are generally accompanied by the strong absorption of the terrestrial water. As we will see using the simulation, the lines with the intermediate strength contribute to the total planetary signal.

### 2.3. Night Airglow and Instrumental Noises

In equation (8), we neglected the term of the night airglow, $S_{sky}$. The intensity of the night airglow strongly depends on the observing band. We compare the intensity of the night airglow $I_{sky} = S_{sky} \Delta \Omega$ with the speckle intensity $I_{speckle}$. If assuming the aperture with a radius $\theta = \lambda/D$ and $D = 30$ m, the median, mean and maximum magnitude of the airglow are (median, mean, maximum)=(29.27, 23.27) for the I-band, (25.29, 19.19) for the J-band, and (27, 21, 15) for the H-band. Because the intensity of the speckle is 300 – 30000 times larger than the planetary flux for our case, the photon noise of the night airglow even for the maximum value is negligible for the I-band (see Table 2). However, the strong airglow lines in the J- and H-band may exceed the speckle noise in photon counts at the wavelength of these lines.

Because there are not so much those strong lines fortunately, we can mask them when analyzing the spectra. In next section, we include the night airglow spectra in the simulations to examine its effect.

The instrumental noises, especially, the readout noise and the dark current depend on what type of the detector we assume. For the water detection, we assume that the speckle noise is $300 \sim 30000$ times larger than the planet flux, we will obtain hundreds to several ten-thousands for a 30 m telescope and the 10 % efficiency. Hence, we can ignore the photon noise of the readout noise and the dark current for most case. For the extremely raw contrast $\sim 10^{-7.5}$ case for the ELT around G-type stars with $C_{ps} \sim 10^{-10}$, the photon counts is several hundreds per hr per bin. In this case, one should use the detector with the low noise level.

### 3. CROSS-CORRELATION ANALYSIS OF THE SIMULATED NIR SPECTRA OF THE ELPS

#### 3.1. Mock planetary systems and Observational Configuration

To simulate the spectra, we set the mock planetary systems as summarized in Table 3. We consider planets in the HZ around M and G-type stars. Those are dubbed #M and #G in this paper. Distance to the system is set to 5 pc for #M and 10 pc for #G. We note that there are ~ 40 M-type stars within 5 pc and 26 G-type stars within 10 pc from the Earth.

For #M, we assume an early M-type star with the effective temperature $T_\star = 3500$ K, the stellar mass $M_\star = 0.5M_\odot$, and the stellar luminosity $L_\star = 0.019L_\odot$ (logg=5.0 and the stellar radius $R_\star = 0.37R_\odot$). The corresponding HZ is 0.15 - 0.3 au (Kopparapu et al. 2013). We decide to use the inner edge as is the case for the Earth, $a=0.15$ au, as the semimajor axis of the planet. The maximum angular separation for a circular orbit is 30 mas at 5 pc, corresponding to 2.4-5.5 $\lambda/D$ for 0.8-1.8 $\mu$m with $D = 30$ m. The next-generation high-contrast instruments will significantly reduce the stellar speckles in this angular separation range (e.g. Guvon et al. 2012). The planetary system we assume is similar to Kepler-186 system (Quintana et al. 2014), GJ 667C (Anglada-Escudé et al. 2013), and GJ 832c (Wittenmyer et al. 2014) in a planet within/close to the HZ around the M-type stars. For #G, we mock the Sun-Earth system, i.e. $T_\star = 5750$ K, $M_\star = M_\odot$, $L_\star = L_\odot$, $R_\star = R_\odot$ and $a = 1$ au.

Because the aim of the paper is to see how the method work for the Earth-analog, the planet has the Earth radius and the same structure as the terrestrial atmosphere even for # M although the atmospheric structure depends on the stellar type due to the UV environment (Segura et al. 2010) and the tidal locking (e.g. Joshi et al. 1997; Merlis & Schneider 2010; Yang et al. 2013).

The relative velocity of the planetary system to the observer is set to 20 km/s. In reality, this velocity includes the orbital radial velocity of the Earth ($\sim 30$ km/s as the orbital velocity) and the relative velocity between the Sun and the observed system. The relative radial velocity of the planet to the system is set to 30 km/s for #M and 20 km/s for #G so as to reproduce the typical radial velocity of the planet in the HZ with the intermediate value of the orbital inclination $i \sim 45^\circ$. 

Doppler-shifted Water and Oxygen of ELPs

Table 3
Stellar and Planetary Properties of the Mock Systems

| label | #M | #G |
|-------|----|----|
| Host Star | | |
| $T_*$ [K] | 3500 | 5750 |
| $d$ [pc] | 5 | 10 |
| $R_*$ | $0.37 R_\odot$ | $1 R_\odot$ |
| log$g$ | 5.0 | 4.5 |
| metallicity Z | $Z_\odot$ | $Z_\odot$ |
| magnitude I,J,H | 6.5,5.7,5.0 | 4.0,3.7,3.3 |
| $V_{sys}$ | 20 km/s | 20 km/s |

| Planet in the HZ | |
|------------------|------------------|
| $V_p$ | 30 km/s | 20 km/s |
| $R_p$ | $R_\odot$ | $R_\odot$ |
| $a$ | 0.15 au | 1.0 au |
| $\theta$ | 30 mas | 100 mas |
| $C_{\text{ps}}^\dagger$ | $\sim 5 \times 10^{-9}$ | $\sim 1 \times 10^{-10}$ |

$\dagger$: the maximum angular separation.
*: results from the simulations.

Table 4
Instrumental Configuration

| symbol | value |
|--------|-------|
| Telescope diameter | $D$ | 30 m |
| Total throughput | $\eta$ | 0.1 |
| Resolving power | $R$ | 50,000 |
| Band for water detection | $0.8-1.8 \mu m$ |
| Band for oxygen detection | $1.27 \mu m$ |
| Band for the scattered stellar lines | $0.8-1.8 \mu m$ |

| Raw contrast | $C_{\text{raw}}$ | $10^{-4} - 10^{-5}$ |
| Exposure time | $T_{\text{exp}}$ | 20 days |

| Raw contrast | $C_{\text{raw}}$ | $10^{-6.5} - 10^{-7.5}$ |
| Exposure time | $T_{\text{exp}}$ | 20 days |

3.2. Radiative Transfer

To simulate both the scattered spectra of the ELP and the terrestrial transmittance of our Earth, we use the radiative transfer code, libradtran with the line-by-line scheme (LBL). The LBL optical depth is computed by pyCAT, from the line parameter database, HITRAN2012. The LBL optical depth includes the molecular lines of water (H$_2$O), oxygen (O$_2$), carbon dioxide (CO$_2$) and nitrous oxide (N$_2$O). The AFGL atmospheric constituent profile (U.S. standard atmosphere 1976) is used for the atmospheric structure.

We use the stellar spectral models provided by Coelho et al. (2003) as the input stellar input flux. The spectral resolution of those templates is $\Delta \lambda = 0.002$ nm ($R \sim 5 \times 10^5$ at 1 $\mu m$), which is sufficiently high for our purpose. The planetary flux is directly derived from radiance computed by the radiative transfer. To reduce the computation time, we use the representative geometry, instead of considering all of facets on the planetary surface, which has the solar-zenith angle = 60°, the azimuth angle of the in- and out-cutting rays = 180° and the view zenith angle = 30°, roughly corresponding to the central position of the visible and illuminated area of the planet when the star-planet-observer angle is $\beta = 90^\circ$. We computed both the clear-sky spectrum and the cloudy-sky spectrum and took an average of them (the cloud fraction is 50%). We assume the water clouds with the optical depth of 20 and the altitude of 2-4 km. The ground albedo was set to 0.1 so as to reproduce the planetary albedo of our Earth, $A \sim 0.3$.

The terrestrial transmittance at the 4 km altitude from the sea level is also computed by the same setting of the radiative transfer as the clear-sky case. Considering the long exposure of the target, we determine to use 45 degree as the representative altitude of the observation. The simulated night airglow spectrum is taken from the gemini website (Lord, S.D. 1992, NASA Technical Memor. 103957 and Gemini Observatory). We use the Mauna-kea sky emission with airmass=1.5 and water vapor column=1.0 mm.

Figure 1. Examples of the simulated NIR spectra. From top to bottom, $F_\text{pl}(\lambda)$ and $F_\text{pl}(\lambda)$ for #M, the night airglow, the transmittance $T(\lambda)$ at the 4 km/s altitude where the telescope is located, and the total spectrum, $f_{\text{tot}}$ for $C_{\text{raw}} = 10^{-5}$ are shown. The spectral resolution is $\Delta \lambda = 0.002$ nm (blue). The green lines are smoothed by the binning with the width of 1 nm.

Figure 4 shows an example of the simulated spectra. We combine the planetary spectra, the stellar spectra, the terrestrial transmittance, and the airglow according to equations (2) and (3) as shown in the bottom panel of Figure 4. The instrumental noise $f_{\eta}$ is neglected. The spectra are binned with the spectral resolution $R = 50,000$. The expected number of photons for each bin is computed based on the telescope diameter of $D$, the exposure time $T_{\text{exp}}$, and the total throughput $\eta$. We added the shot noise to the spectra according to the Poisson distribution.

4 http://www.libradtran.org
5 See the website of libradtran for the detail.
Before analyzing the mock spectra, we demonstrate how the planetary lines are separated from the terrestrial absorption lines using this simulation. Figure 2 shows the unabsorbed planetary spectrum, the terrestrial transmittance, and the planetary spectrum after the transmission through the terrestrial atmosphere. As shown by the green and red vertical lines that indicate the wavelength of the strong water lines in the Doppler-shifted frame and in the rest frame, the water vapor lines from the exoplanets after the terrestrial transmittance can be separated from the terrestrial one if the transmittance is not very large. The high-dispersion spectroscopy has the same virtue for other terrestrial biosignatures, such as oxygen, carbon dioxide.

3.3. Data Reduction and Cross-Correlation Function Analysis

Both the terrestrial transmittance spectrum and the speckle spectrum are deduced from the combined spectra to increase the signal from the planetary lights. In principle, those spectra can be estimated by the simultaneous observation of the speckles at no planet position and the sophisticated method to fit the terrestrial transmittance. There can be several possible sources of the systematics in that procedure, i.e., uncertainty of the stellar speckle spectrum, the night airglow, and the terrestrial transmittance. In this paper, we mainly focus on the most optimistic case, the photon noise limit: we know the accurate speckle stellar spectra and the terrestrial transmittance. There can be several possible sources of the systematics in that procedure, i.e., uncertainty of the stellar speckle spectrum, the night airglow, and the terrestrial transmittance. In this paper, we mainly focus on the most optimistic case, the photon noise limit: we know the accurate speckle stellar spectra and the terrestrial transmittance. There can be several possible sources of the systematics in that procedure, i.e., uncertainty of the stellar speckle spectrum, the night airglow, and the terrestrial transmittance. In this paper, we mainly focus on the most optimistic case, the photon noise limit: we know the accurate speckle stellar spectra and the terrestrial transmittance.

3.4. Detectability of Water Vapor

In the NIR band, there are numerous water vapor lines over a wide range of the line strength. The most effective way to extract the molecular signal is to use the template spectrum adequately simulated by the radiative transfer. However, in general, we do not utilize any information on the atmospheric structure of the exoplanet. Hence, we use the binary template of the molecular lines above the given line strength $u_{\text{lim}}$: for the $i$-th line with the line strength $u_i(A_i) \geq u_{\text{lim}}$, $g_i(A_i) = 0$, otherwise 1. The binary templates are created based on HITRAN2012. Water vapor has an enormous number of molecular lines in the visible and infrared bands. If the binary template includes all lines, the CCF signal becomes very small. Hence we must choose an adequate criterion of the line strength. We find that $u_{\text{lim}} = 10^{-24}$ cm$^{-1}$/cm$^{-2}$ covers...
most strong lines of the scattered light (see also Figure 2). To mask the wavelength regions that exhibit large photon noises, we exclude the ranges where the terrestrial extinction is high (the gray regions in Figure 3). As the result of this masking procedure, most of water lines with the line strength above $10^{-22} \text{cm}^{-1} \text{cm}^{-2}$ are eliminated. We confirmed that this procedure is crucial to increase the signal to noise ratio. Hence, this method mainly uses the water vapor lines with the intermediate strength with $10^{-24} - 10^{-22} \text{cm}^{-1} \text{cm}^{-2}$.

The left panel in Figure 4 displays the CCFs of the mock spectra with the binary template of water for #M. The CCFs exhibit a clear feature of the Doppler-shifted water lines at $v = V_p + V_{\text{sys}}$. Because the peak has ~ two bins of the width, we take average of the CCF over each two bins and computed the standard-deviation between two bins of the width, we take average of the CCF over each.

We also perform the CCF analysis of water vapor for #G (the right panel in Figure 4). For the extraction of the scattered stellar lines, the stellar spectrum itself is used as the template $g_i(\lambda) = F_i(\lambda)$. This template naturally includes the velocity of the system, $v = V_{\text{sys}}$. Hence, one find the CCF signal at $v = V_p$ because of the relative velocity of the star and the planet. In this simulation, we find that the CCF exhibits a clear feature of the scattered stellar lines for $C_{\text{raw}} = 10^{-5}$.

Although the scattered stellar lines do not have the information on the planetary atmosphere, the detection of those lines will be a direct evidence of the scattered light from the planet. The scattered stellar lines also have the advantage that the signal does not directly depend on the atmospheric composition of the planet. Considering the blind search for planets, this virtue is remarkable. Because of the focus of this paper on characterization of the ELP, we postpone the detailed analysis of the scattered stellar lines to a forthcoming paper (Kawahara et al. in preparation).

3.6. Detectability of Scattered Stellar Lines

For the extraction of the scattered stellar lines, the stellar spectrum itself is used as the template $g_i(\lambda) = F_i(\lambda)$. This template naturally includes the velocity of the system, $v = V_{\text{sys}}$. Hence, one find the CCF signal at $v = V_p$ because of the relative velocity of the star and the planet. In this simulation, we find that the CCF exhibits a clear feature of the scattered stellar lines for $C_{\text{raw}} = 10^{-5}$.

Although the scattered stellar lines do not have the information on the planetary atmosphere, the detection of those lines will be a direct evidence of the scattered light from the planet. The scattered stellar lines also have the advantage that the signal does not directly depend on the atmospheric composition of the planet. Considering the blind search for planets, this virtue is remarkable. Because of the focus of this paper on characterization of the ELP, we postpone the detailed analysis of the scattered stellar lines to a forthcoming paper (Kawahara et al. in preparation).

3.7. Sensitivity to Systematics

So far, we have assumed that we can perfectly estimate the stellar speckle, terrestrial transmission, and the night airglow. Here, we investigate the sensitivity of the result to the accuracy of those estimates. Changing the true spectrum $f_{\text{speckle}}(\lambda)$ to the inaccurate one $f'_{\text{speckle}}(\lambda)$ in

We do not include any broadening effect in this paper. Hence, the results for the scattered stellar lines are valid only for the slow-rotator with $V \sin \ i \leq 6 \text{ km/s}$.
Figure 4. The CCFs with the binary template of the water vapor with $u_{\text{lim}} = 10^{-24}\text{cm}^{-1}/\text{cm}^{-2}$ for $\# M$ at 5 pc (left) and $\# G$ at 10 pc (right). The bottom to top curves correspond to the raw contrast $C_{\text{raw}} = 10^{-4}, C_{\text{raw}} = 10^{-4.5}$, and $C_{\text{raw}} = 10^{-5}$ using the whole band, 0.8-1.8 $\mu$m (I+Y+J+H). The top and bottom curves are artificially shifted by 0.04 and -0.04 in the $y-$ direction.

Figure 5. The dependence on the bands used to the CCF analysis of the water vapor for $\# M$. From bottom to top, I,Y,J, and H-bands are used. This figure assumes the raw contrast $C_{\text{raw}} = 10^{-5}$. The curves corresponding to I,Y and H bands are artificially shifted in the $y-$ direction.

Figure 6. The CCFs with the oxygen 1.27 $\mu$m binary template with $u_{\text{lim}} = 10^{-27}\text{cm}^{-1}/\text{cm}^{-2}$ for $\# M$. The bottom (red) and top (blue) curves correspond to $C_{\text{raw}} = 10^{-5}, C_{\text{raw}} = 10^{-5}$. To clearly show the structure of the CCF, we also show the CCF for $C_{\text{raw}} = 10^{-6}$ (gray). The top and bottom curves are artificially shifted by 0.015 and -0.015 in the $y-$ direction.

Figure 8). The night airglow subtraction is less sensitive to the CCFs than that the speckle subtraction, i.e. $\sim \pm 5\%$ of uncertainty is allowed for $\# M$ with $C_{\text{raw}} = 10^{-4.5}$.

The sensitivity to the accuracy of the terrestrial transmission estimate is also examined. We add the additional errors to the transmittance for the strong water (the line strength $> 10^{-24}\text{cm}^{-1}/\text{cm}^{-2}$) and oxygen (the line strength $> 10^{-27}\text{cm}^{-1}/\text{cm}^{-2}$). We also systematically increase/decrease the transmittance for the strong lines. However, the results are unchanged even for adding the 50% rms random error or the 10% systematic changes. To see why the CCFs is insensitive to the accuracy of the transmittance, instead of equation (12), we test the extreme case, computing the CCF with no transmittance.
obtained although one can do that in principle.

In short summary, the accuracy of the speckle spectrum subtraction is the most crucial for this method.

4. DISCUSSION AND SUMMARY

As examined in the previous section, our method needs a long exposure to detect the signal. What are the advantages of this method compared to the low-resolution spectroscopy by direct imaging from ground? One is that our method requires no additional post-processing to improve the contrast from the raw contrast by ExAO+coronagraph or in other words, this method is the post-processing itself. This feature is remarkable because for the low-resolution spectroscopy for the ELPs from ground, the post-processing must improve the final contrast to the planet-star contrast level of $10^{-8}$ from the raw contrast. As far as we know, there is no full simulation that presents the evidence that the ExAO+coronagraph with the post processing improves the contrast of the order of $5 \times 10^{-4}$ from the raw contrast (considering $C_{ps} = 5 \times 10^{-9}$ and $C_{raw} = 10^{-4}$ used in our simulations) yet. Another point is the simpleness of the calibrations as discussed in §3.5 and 3.7. The low-resolution spectroscopy requires very careful calibrations of the night airglow and the terrestrial transmittance because those are directly related to the estimate of the depth of the absorption feature for the low-resolution case (Kawahara et al. 2012). Hence, even after the post processing reaches the planet-star contrast of the ELPs, our method is complementary and will make the molecular detection robust.

If significant progress of the ExAO will enable us to improve the raw contrast to $10^{-6}$ at 30 mas, one can search for water vapor in 5 hours from equation (11). This will open the possibility of the water planet survey with our method in future.
strongest water signal among 0.8-1.8 \mu m (Figure 5). The J-band also has the oxygen 1.27 \mu m band in it. We also note that the performance of the ExAO will be higher around the J- and H-band due to the wavelength dependence of the wavefront error. For these reasons, we suggest the J-band as the most fruitful band for this method. In our simulation, the CCFs with $C_{\text{raw}} = 10^{-4.5}$ exhibits a clear feature of the water vapor $4.5 \sigma$ and an evidence of the oxygen with $\sim 2.3 \sigma$ for \#M. Hence the J-band with $C_{\text{raw}} = 10^{-4.5}$ is a good starting point.

This paper assumes long exposure (20 days) for the characterization of the ELP. Hence, our method might not be suitable for the survey. The point we should consider is how we choose the adequate candidates for the long observing campaign. The direct imaging using the ELTs is one of promising ways to find the target (e.g. Macintosh et al. 2006; Matsuo & Tamura 2010; Kasper et al. 2010; Guyon et al. 2012; Crossfield 2013; Males et al. 2014). Assuming ETIs and the PIAACMC coronagraph, Guyon et al. (2012) presented the technological solutions to reach the rocky planets around nearby M dwarfs. Crossfield (2013) presented the detectability of the planets assuming the ExAO on the ELT and the contrast improvement by the post-processing. Utilizing the frequencies the low mass planets from the Kepler mission, he found that $\sim 10$ planets with $R_p = 1 - 8R_\oplus$ with the radiative equilibrium temperature $T_{\text{eq}} \leq 400$ K can be accessible with ELTs. Those planets will be excellent targets for our method. If the planet is detected by both the radial velocity and the astrometry, a long observation at the planet position predicted by those detection methods is possible without the direct imaging. However, when only the radial velocity is available, our method becomes more challenging. For this case, we have no information on the position angle. To apply our method to those planets, integral field spectroscopy with $R \sim 50,000$ is required.

The detection of the water lines does not mean the presence of the surface liquid water. Regarding the search for the liquid water, the diagnosis proposed by Fujii et al. (2015) is a promising option. They suggested a difference in the diurnal variability of water vapor and oxygen lines as an evidence of the existence of the surface liquid water. In this paper, we did not include the surface inhomogeneity in our simulations and we might require the information on the rotation period to stack the signal to extract the variability. More detailed simulations are required to explore the possibility of further characterization of the ELP with the combination of the high-dispersion and high-contrast instruments.

In summary, we proposed a method to characterize both the non-transiting and transiting ETIs via the Doppler-shifted water vapor and oxygen lines using the high-dispersion spectroscopy and the high-contrast instruments on the ELTs. This method requires no additional post-processing from the raw contrast. Performing the mock observations using the radiative transfer code for the Earth, we examined the feasibility of the method assuming the ELTs. A long observing campaign with the total exposure 20 days can detect the water vapor lines on nearby ETIs around M-type stars if the high contrast instruments suppress the speckle in the level of $10^{-4} - 10^{-5}$ at 30 mas. If the raw contrast reaches $10^{-5}$, the oxygen 1.27 \mu m feature is also detectable. For the ELP around solar-type stars, one need several hundreds better contrasts at $\sim 100$ mas. A combination of the high-dispersion and high-contrast instruments on the ELTs will enable us to characterize the nearby exoplanets even for Earth-sized planets within the HZ.

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REFERENCES

Anglada-Escudé, G., et al. 2012, ApJ, 751, L16
Artigau, E., et al. 2014, arXiv:1406.6992
Birkby, J. L., de Kok, R. J., Brogi, M., de Mooij, E. J. W., Schwarz, H., Albrecht, S., & Snellen, I. A. G. 2013, MNRAS, 436, L35
Brandl, B. R., et al. 2014, arXiv:1409.3087
Brogi, M., de Kok, R. J., Birkby, J. L., Schwarz, H., & Snellen, I. A. G. 2014, A&A, 565, A124
Coelho, P., Barbuy, B., Maldonado, J., Schiavon, R. P., & Castilho, B. V. 2005, A&A, 443, 735
Crossfield, I. J. M. 2013, A&A, 551, A99
Des Marais, D. J., et al. 2002, Astrobiology, 2, 153
Fujii, Y., Turner, E. L., & Suto, Y. 2013, ApJ, 765, 76
Guyon, O. 2005, ApJ, 629, 592
Guyon, O., Martinache, F., Cadiz, E. J., Belikov, R., Balasubramanian, K., Wilson, D., Clergeon, C. S., & Mateen, M. 2012, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 8447, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series
Joshu, M. M., Haberle, R. M., & Reynolds, T. R. 1997, Icarus, 129, 450
Kaltenegger, L., Traub, W. A., & Jucks, K. W. 2007, ApJ, 658, 598
Kasper, M., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7735, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series
Kawahara, H. 2012, ApJ, 760, L13
Kawahara, H., Matsuo, T., Takami, M., Fujii, Y., Kotani, T., Murakami, N., Tamura, M., & Guyon, O. 2012, ApJ, 758, 13
Kawahara, H., Murakami, N., Matsuo, T., & Kotani, T. 2014, ApJS, 212, 27
Koppapurapu, R. K., et al. 2013, ApJ, 765, 131
Korkiaikoski, V., & Verinaud, C. 2010, in Adaptive Optics for Extremely Large Telescopes
Kotani, T., et al. 2014, in SPIE Astronomical Telescopes+ Instrumentation, International Society for Optics and Photonics, 914714
Lockwood, A. C., Johnson, J. A., Bender, C. F., Carr, J. S., Barman, T., Richert, A. J. W., & Blake, G. A. 2014, ApJ, 783, L29
Macintosh, B., et al. 2006, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 6272, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series
Males, J. R., et al. 2014, arXiv:1407.5099
Martins, J. H. C., Figueira, P., Santos, N. C., & Lovis, C. 2013, MNRAS, 436, 1215
Matsuo, T., & Tamura, M. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7735, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series
Mayer, B., Kylling, A., et al. 2005, Atmospheric Chemistry and Physics Discussions, 5, 1319
Merlis, T. M., & Schneider, T. 2010, Journal of Advances in Modeling Earth Systems, 2, 13
Pepe, F. A., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7735, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series
Quintana, E. V., et al. 2014, Science, 344, 277
Quirrenbach, A., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7735, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series
Rodler, F., & López-Morales, M. 2014, ApJ, 781, 54
Rothman, L. 1999, NEWSLETTER, 6
Segura, A., Walkowicz, L. M., Meadows, V., Kasting, J., & Hawley, S. 2010, Astrobiology, 10, 751
Snellen, I. A. G., Brandl, B. R., de Kok, R. J., Brogi, M., Birkby, J., & Schwarz, H. 2014, Nature, 509, 63
Snellen, I. A. G., de Kok, R. J., le Poole, R., Brogi, M., & Birkby, J. 2013, ApJ, 764, 182
Sobolev, V. V. 1975, Light scattering in planetary atmospheres
Spinrad, H., Münch, G., & Kaplan, L. D. 1963, ApJ, 137, 1319
Turnbull, M. C., Traub, W. A., Jucks, K. W., Woolf, N. J., Meyer, M. R., Gorlova, N., Skrutskie, M. F., & Wilson, J. C. 2006, ApJ, 644, 551
Wittenmyer, R. A., et al. 2014, ApJ, 791, 114
Yang, J., Cowan, N. B., & Abbot, D. S. 2013, ApJ, 771, L45