SPECTRAL FINGERPRINTS OF EARTH-LIKE PLANETS AROUND FGK STARS

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ABSTRACT

We present model atmospheres for an Earth-like planet orbiting the entire grid of main sequence FGK stars with effective temperatures ranging from $T_{\text{eff}} = 4250K$ to $T_{\text{eff}} = 7000K$ in 250K intervals. We model the remotely detectable spectra of Earth-like planets for clear and cloudy atmospheres at the 1AU equivalent distance from the VIS to IR (0.4 µm - 20 µm) to compare detectability of features in different wavelength ranges in accordance with JWST and future design concepts to characterize exo-Earths. We also explore the effect of the stellar UV levels as well as spectral energy distribution on a terrestrial atmosphere concentrating on detectable atmospheric features that indicate habitability on Earth, namely: H2O, O3, CH4, N2O and CH3Cl.

The increase in UV dominates changes of O3, OH, CH4, N2O and CH3Cl whereas the increase in stellar temperature dominates changes in H2O. The overall effect as stellar effective temperatures and corresponding UV increase, is a lower surface temperature of the planet due to a bigger part of the stellar flux being reflected at short wavelengths, as well as increased photolysis. Earth-like atmospheric models show more O3 and OH but less stratospheric CH4, N2O, CH3Cl and tropospheric H2O (but more stratospheric H2O) with increasing effective temperature of Main Sequence stars. The corresponding spectral features on the other hand show different detectability depending on the wavelength observed.

We concentrate on directly imaged planets here as framework to interpret future lightcurves, direct imaging and secondary eclipse measurements of atmospheres of terrestrial planets in the HZ at varying orbital positions.

Key Words: Habitability, Planetary Atmospheres, Extrasolar Terrestrial Planets, Spectroscopic Biosignatures

1. INTRODUCTION

Over 830 extrasolar planets have been found to date with thousands more candidate planets awaiting confirmation from NASA’s Kepler Mission. Several of these planets have been found in or near the circumstellar Habitable Zone (see e.g. Batalha et al., 2012; Borucki et al. 2011, Udry et al., 2007; Kaltenegger & Sasselov 2011) with masses and radii consistent with rocky planet models. Recent radial velocity results as well as Kepler demonstrate that small planets in the Habitable Zone (HZ) exist around solar type stars. Future mission concepts to characterize Earth-like planets are designed to take spectra of extrasolar planets with the ultimate goal of remotely detecting atmospheric signatures (e.g., Beichman et al., 1999, 2006; Cash 2006; Traub et al., 2006). For transiting terrestrial planets around the closest stars, the James Web Space Telescope (JWST, see Gardner et al., 2006) as well as future ground and space based telescopes might be able to detect biosignatures by adding multiple transits for the closest stars (see discussion).

Several groups have explored the effect of stellar spectral types on the atmospheric composition of Earth-like planets by considering specific stars: F9V and K2V (Selsis, 2000); F2V and K2V (Segura et al., 2003; Grenfell et al., 2007; Kitzmann et al., 2011ab). In this paper we expand on this work by establishing planetary atmosphere models for the full FGK main sequence, using a stellar temperature grid from 7000K to 4250K, in increments of 250K, to explore the effect of the stellar types on terrestrial atmosphere models. We show the effects of stellar UV and stellar temperature on the planet’s atmosphere individually to understand the overall effect of the stellar type on the remotely detectable planetary spectrum from 0.4-20 µm for clear and cloudy atmosphere models.. This stellar temperature grid covers the full FGK spectral range and corresponds roughly to F0V, F2V, F5V, F7V, F9V/G0V, G2V, G8V, K0V, K2V, K4V, K5V and K7V main sequence stars (following the spectral type classification by Gray, 1992).

In this paper we use “Earth-like”, as applied to our models, to mean using modern Earths outgassing rates (following Segura et al. 2003). We explore the influence of stellar spectral energy distribution (SED) on the chemical abundance and planetary atmospheric spectral features for Earth-like planets including biosignatures and their observability from the VIS to IR. Atmospheric biosignatures are chemical species in the atmosphere that are out of chemical equilibrium or are byproducts of life processes. In our analysis we focus particularly on spectral features of
1.1 Photochemistry for Earth-like planets including potential biosignatures

For an Earth-like biosphere, the main detectable atmospheric chemical signatures that in combination could indicate habitability are \( \text{O}_2/\text{O}_3 \) with \( \text{CH}_4/\text{N}_2\text{O} \) and \( \text{CH}_3\text{Cl} \). Note that one spectral feature e.g. \( \text{O}_2 \) does not constitute a biosignature by itself as the planetary context (like bulk planet, atmospheric composition and planet insulation) should be taken into account to interpret this signature. Detecting high concentrations of a reducing gas concurrently with \( \text{O}_2 \) or \( \text{O}_3 \) can be used as a biosignature since reduced gases and oxygen react rapidly with each other. Both being present in significant and therefore detectable amounts in low resolution spectra implies a strong source of both. In the IR, \( \text{O}_3 \) can be used as a proxy for oxygen at \( 10^2 \) Present Atmospheric Level of \( \text{O}_2 \), the depth of the 9.6 \( \mu \text{m} \) \( \text{O}_3 \) feature is comparable to the modern atmospheric level (Kasting et al., 1985; Segura et al., 2003). At the same time, because of the 9.6 \( \mu \text{m} \) \( \text{O}_3 \) feature’s non-linear dependence on the \( \text{O}_2 \) concentration, observing in the visible at 0.76 \( \mu \text{m} \) would be a more accurate \( \text{O}_2 \) level indicator, but requires higher resolution than detecting \( \text{O}_3 \).

\( \text{N}_2\text{O} \) and \( \text{CH}_3\text{Cl} \) are both primarily produced by life on Earth with no strong abiotic sources, however, their spectral features are likely too small to detect in low resolution with the first generation of missions. While \( \text{H}_2\text{O} \) or \( \text{CO}_2 \) are not considered biosignatures as both are produced through abiotic processes, they are important indicators of habitability as raw materials and can indicate the level of greenhouse effect on a planet. We refer the reader to other work (e.g. Des Marais et al., 2006; Meadows 2006; and Kaltenegger et al., 2010b) for a more in depth discussion on habitability and biosignatures. In this section we briefly discuss the most important photochemical reactions involving: \( \text{H}_2\text{O}, \text{O}_3, \text{O}_3, \text{CH}_4, \text{N}_2\text{O}, \text{and CH}_3\text{Cl} \).

Water, \( \text{H}_2\text{O} \): Water vapor is an important greenhouse gas in Earth’s atmosphere. Over 99% of \( \text{H}_2\text{O} \) vapor is currently in the troposphere, where it is an important source of OH via the following set of reactions:

\[
\text{O}_3 + \text{hv} \rightarrow \text{O}_2 + \text{O}^{(1)}(D) \quad \text{[RI]}
\]

\[
\text{H}_2\text{O} + \text{O}^{(1)}(D) \rightarrow 2\text{OH} \quad \text{[R2]}
\]

In the troposphere, the production of \( \text{O}^{(1)}(D) \) takes place for 3000 \( \text{Å} < \lambda < 3200 \text{ Å} \), the lower limit of which is set by the inability of wavelengths, \( \lambda \), shorter than 3000 Å to reach the troposphere due to \( \text{O}_3 \) shielding. \( \text{H}_2\text{O} \), while photochemically inert in the troposphere, can be removed by photolysis primarily by wavelengths shortward of 2000 Å in the stratosphere. The photodissociation threshold energy is 2398 Å, but the cross-section of the molecule above 2000 Å is very low. Stratospheric \( \text{H}_2\text{O} \) can be transported from the troposphere or be formed in the stratosphere by \( \text{CH}_4 \) and \( \text{OH} \).

\[
\text{CH}_4 + \text{OH} \rightarrow \text{CH}_3 + \text{H}_2\text{O} \quad \text{[R3]}
\]

Oxygen and Ozone, \( \text{O}_2 \) and \( \text{O}_3 \): In an atmosphere containing \( \text{O}_2, \text{O}_3 \) concentrations are determined by the absorption of ultraviolet (UV) light shortward of 2400 Å in the stratosphere. \( \text{O}_3 \) is an oxidizing agent more reactive than \( \text{O}_2 \), the most stable form of oxygen, due to the third oxygen atom being loosely bound by a single bond. \( \text{O}_3 \) is also an indirect measure of OH since reactions involving \( \text{O}_3 \) and \( \text{H}_2\text{O} \) are sources of OH. OH is very reactive and is the main sink for reducing species such as \( \text{CH}_4 \). \( \text{O}_3 \) is formed primarily by the Chapman reactions (1930) of the photolysis of \( \text{O}_2 \) by UV photons (1850 Å < \( \lambda \) < 2420 Å) and then the combining of \( \text{O}_2 \) with \( \text{O} \).

\[
\text{O}_2 + \text{hv} \rightarrow \text{O} + \text{O}^{(1)}(\lambda < 240\text{nm}) \quad \text{[R4]}
\]

\[
\text{O} + \text{O}_2 + \text{M} \rightarrow \text{O}_3 + \text{M} \quad \text{[R5]}
\]

\[
\text{O}_3 + \text{hv} \rightarrow \text{O}_2 + \text{O}^{(1)}(\lambda < 320\text{nm}) \quad \text{[R6]}
\]

\[
\text{O}_3 + \text{O} \rightarrow 2\text{O}_2 \quad \text{[R7]}
\]

where \( \text{M} \) is any background molecule such as \( \text{O}_2 \) or \( \text{N}_2 \). Reactions [R5] and [R6] are relatively fast compared with [R4] and [R7] which are the limiting reactions in Earth’s atmosphere. However, considering the Chapman mechanism alone would overpredict the concentration of \( \text{O}_3 \) by a factor of two on Earth. Hydrogen oxide (\( \text{HO}_3 \)), nitrogen oxide (\( \text{NO}_3 \)), and chlorine (\( \text{ClO}_3 \)) radicals are the additional sinks controlling the \( \text{O}_3 \) abundance (Bates & Nicolet, 1950; Crutzen, 1970; Molina and Rowland, 1974, respectively), with \( \text{NO}_3 \) and \( \text{HO}_3 \) being the dominant and second-most dominant sink, respectively.

Methane, \( \text{CH}_4 \): Since \( \text{CH}_4 \) is a reducing gas, it reacts with oxidizing species and thus has a short lifetime of around 10-12 years in modern Earth’s atmosphere (Houghton et al. 2004). In both the troposphere and stratosphere, \( \text{CH}_4 \) is oxidized by OH, which is the largest sink of the global methane budget. In the stratosphere, \( \text{CH}_4 \) is also destroyed by UV radiation. Though its photodissociation energy is 2722 Å, its absorption cross-section isn’t sufficient for \( \lambda > 1500 \text{ Å} \). \( \text{CH}_4 \) is produced biotically by methanogens and termites, and abiotically through hydrothermal vent systems. In the modern atmosphere there is a significant anthropogenic source of \( \text{CH}_4 \) from natural gas, livestock, and rice paddies. \( \text{CH}_4 \) is 25x more effective as a greenhouse gas than \( \text{CO}_2 \) in modern Earth’s atmosphere (Forster et al., 2007) and may have been much more abundant in the early Earth (see e.g. Pavlov et al., 2003).

Nitrous Oxide, \( \text{N}_2\text{O} \): Nitrous oxide, \( \text{N}_2\text{O} \), is a relatively minor constituent of the modern atmosphere at around 320 ppbv, with a pre-industrial concentration of 270 ppbv (Forster et al., 2007). It is important for stratospheric chemistry since around 5% is converted to NO, an important sink of \( \text{O}_3 \), and 95% produces \( \text{N}_2 \).

\[
\text{N}_2\text{O} + \text{O}^{(1)}(D) \rightarrow 2\text{NO} \quad \text{[R8]}
\]
On current Earth, N$_2$O is emitted primarily by denitrifying bacteria with anthropogenic sources from fertilizers in agriculture, biomass burning, industry and livestock.

Methyl Chloride, CH$_3$Cl: CH$_3$Cl has been proposed as a potential biosignature because its primary sources are marine organisms, reactions of sea foam and light, and biomass burning (Segura et al., 2005). The primary loss of CH$_3$Cl in Earth’s atmosphere is by OH as seen in [R9], but it can also be photolyzed or react with atomic chlorine. Because CH$_3$Cl is a source of chlorine in the stratosphere, it also plays a role in the removal of O$_3$, as discussed earlier.

\[
\begin{align*}
CH_3Cl + OH & \rightarrow Cl + H_2O \quad \text{[R9]} \\
CH_3Cl + \nu & \rightarrow CH_3 + Cl \quad \text{[R10]} \\
CH_3Cl + Cl & \rightarrow HCl + Cl \quad \text{[R11]}
\end{align*}
\]

2. Model Description

We use EXO-P (Kaltenegger & Sasselov 2010) a coupled one-dimensional radiative-convective atmosphere code developed for rocky exoplanets based on a 1D climate (Kasting & Ackerman 1986, Pavlov et al. 2000, Haqq-Misra et al. 2008), 1D photochemistry (Pavlov & Kasting 2002, Segura et al. 2005, 2007) and 1D radiative transfer model (Traub & Stier 1976, Kaltenegger & Traub 2009) to calculate the model spectrum of an Earth-like exoplanet.

2.1 Planetary Atmosphere Model

EXO-P is a model that simulates both the effects of stellar radiation on a planetary environment and the planet’s outgoing spectrum. The altitude range extends to 60 km with 100 layers. We use a geometrical model in which the average 1D global atmospheric model profile is generated using a plane parallel atmosphere, treating the planet as a Lambertian sphere, and setting the stellar zenith angle to 60 degrees to represent the average incoming stellar flux on the dayside of the planet (see also Schindler & Kasting, 2000).

![Figure 1: F0V and K7V composite input stellar spectrum of IUE observations coadded to (black) ATLAS photospheric models (Kurucz, 1979) and (red) binned stellar input. Note: the full input spectrum extends to 45450 Å. Only the hottest and coolest star in our grid are shown here for comparison.](image)

The temperature in each layer is calculated from the difference between the incoming and outgoing flux and the heat capacity of the atmosphere in each layer. If the lapse rate of a given layer is larger than the adiabatic lapse rate, it is adjusted to the adiabat until the atmosphere reaches equilibrium. A two-stream approximation (see Toon et al., 1989), which includes multiple scattering by atmospheric gases, is used in the visible/near IR to calculate the shortwave fluxes. Four-term, correlated-k coefficients parameterize the absorption by O$_3$, H$_2$O, O$_2$, and CH$_4$ in wavelength intervals shown in Fig. 1 (Pavlov et al., 2000). In the thermal IR region, a rapid radiative transfer model (RRTM) calculates the longwave fluxes. Clouds are not explicitly calculated. The effects of clouds on the temperature/pressure profile are included by adjusting the surface albedo of the Earth-Sun system to have a surface temperature of 288K (see Kasting et al., 1984; Pavlov et al. 2000; Segura et al., 2003, 2005). The photochemistry code, originally developed by Kasting et al. (1985) solves for 55 chemical species linked by 220 reactions using a reverse-Euler method (see Segura et al., 2010 and references therein).

The radiative transfer model used to compute planetary spectra is based on a model originally developed for trace gas retrieval in Earth’s atmospheric spectra (Traub & Stier 1976) and further developed for exoplanet transmission and emergent spectra (Kaltenegger et al., 2007; Kaltenegger & Traub, 2009; Kaltenegger 2010; Kaltenegger et al. 2010a). In this paper we model Earth’s reflected and thermal emission spectra using 21 of the most spectroscopically significant molecules (H$_2$O, O$_3$, O$_2$, CH$_4$, CO$_2$, OH, CH$_3$Cl, NO$_2$, N$_2$O, HNO$_3$, CO, H$_2$S, SO$_2$, H$_2$O$_2$, NO, ClO, HOCI, HO$_2$, H$_2$CO, N$_2$O$_3$, and HCl).

Using 34 layers the spectrum is calculated at high spectral resolution, with several points per line width, where the line shapes and widths are computed using Doppler and pressure broadening on a line-by-line basis, for each layer in the model atmosphere. The overall high-resolution spectrum is calculated with 0.1 cm$^{-1}$ wavelength steps. The figures are shown smoothed to a resolving power of 250 in the IR and 800 in the VIS using a triangular smoothing kernel. The spectra may further be binned corresponding to proposed future spectroscopy missions designs to characterize Earth-like planets.

2.2 Model Validation with EPOXI

We previously validated EXO-P from the VIS to the infrared using data from ground and space (Kaltenegger et al., 2007). Here we use new data by EPOXI in the visible and near-infrared (Livengood et al., 2011) for further validation (see Fig. 2). The data set we use to validate our visible and the near-infrared Earth model spectra is the first EPOXI observation of Earth which was averaged over 24 hours on 03/18/2008 – 03/19/2008 and taken at a phase angle of 57.7°. The uncertainty in the EPOXI calibration is ~10% (Klassen et al., 2008). Atmospheric models found the best match to be for a 50% cloud coverage with 1.5km and 8.5km cloud layer respectively (Robinson et al., 2011). Here we use a 60% global cloud cover spectrum divided between three layers: 40% water clouds at 1km, 40% water clouds at 6km, and 20% ice clouds at 12km (following Kaltenegger et al., 2007) consistent with an averaged Earth profile to compare our model to this 24hr data set, which should introduce slight discrepancies. To correct the brightness values to match to our full-phase model we use a
Lambert phase function.

Our model agrees with EPOXI on an absolute scale within 1-3% for the middle photometric points. The largest discrepancies in the visible are at 0.45 µm and 0.95 µm (with a 8% and 18% error respectively).

![Comparison of EPOXI data (red) with the Earth model, top-of-atmosphere spectrum at full phase from EXO-P (black) in the visible (left) and near-infrared (right).](image)

2.3 Stellar Spectral Grid Model

The stellar spectral grid ranges from 4250K to 7000K in effective temperature increments of 250K. This temperature range effectively probes the F0 to K7 main sequence spectral types. For each model star on our grid we concatenated a solar metallicity, unreddened synthetic ATLAS spectrum, which only considers photospheric emission (Kurucz, 1979), with observations from the International Ultraviolet Explorer (IUE) archive. We use IUE measurements to extend ATLAS synthetic spectra, to generate input spectra files from 1150Å to 45,450Å (see Figs. 1 and 2). We choose main sequence stars in the IUE archive with corresponding temperatures close to the grid temperatures and near solar metallicity, as described below.

| Star   | T\text{eff}(K) | T\text{eff}(K) Grid | [Fe/H] | Spectral Type Grid |
|--------|----------------|---------------------|--------|--------------------|
| η Lep  | 7060           | 7000                | -0.13  | F0V                |
| σ Boo  | 6730           | 6750                | -0.43  | F2V                |
| π Ori  | 6450           | 6500                | 0.03   | F5V                |
| τ Psc  | 6240           | 6250                | -0.09  | F7V                |
| β Com  | 5960           | 6000                | 0.07   | F9V/G0V            |
| α Cen A| 5770           | 5750                | 0.21   | G2V                |
| τ Ceti | 5500           | 5500                | -0.52  | G8V                |
| HD 10780 | 5260        | 5250                | 0.03   | K0V                |
| ε Er i | 5090           | 5000                | -0.03  | K2V                |
| ε Ind i| 4730           | 4750                | -0.23  | K4V                |
| 61 Cyg A | 4500        | 4500                | -0.43  | K5V                |
| BY Dra | 4200           | 4250                | 0.00   | K7V                |

Table 1: List of representative IUE stars with their measured T\text{eff}, the T\text{eff} which corresponds to our grid of stars, their metallicity, and their approximate spectral type following Gray (1992).

The IUE satellite had three main cameras, the longwave (LWP/LWR) cameras (1850Å – 3350Å), and the shortwave (SW) camera (1150Å – 1975Å). When preparing the IUE data (following Segura et al., 2003; Massa et al., 1998; Massa & Fitzpatrick, 2000), we used a sigma-weighted average to coadd the multiple SW and LW observations. We used a linear interpolation when there was insufficient high quality measurements to merge the wavelength region from the SW to the LW cameras. IUE measurements were joined to ATLAS model spectra at 3000 Å. In a few cases, a shift factor is needed to match the IUE data to the ATLAS model (see also Segura et al., 2003) but unless stated explicitly no shift factor was used. Effective temperatures and metallicities are taken from NSiED (derived from Flower et al. (1996) and Valenti & Fischer (2005), respectively) unless otherwise cited. See Table 1 for a summary list of the representative IUE stars chosen.

HD 40136, η Lep, is at 15.04pc with T\text{eff} = 7060K and [Fe/H] = -0.13 (Cayrel de Strobel et al., 2001), corresponding to an F0V, the hottest model grid star. Two LW and four SW spectra were coadded and merged with a 7000K ATLAS spectrum.

To compare with previous work (Segura et al., 2003; Grenfell et al., 2007; Selsis, 2000), we chose HD 128167, σ Boötes, for our model F2V grid star. σ Boötes is an F2V star at 15.47pc with T\text{eff} = 6730K and [Fe/H] = -0.43. Two LW and five SW spectra were coadded and merged with a 6750K ATLAS spectrum. A slight downward shift of a factor of 0.88 is necessary to match the IUE data with a ATLAS spectrum (see also Segura et al., 2003).

π Orionis, HD 30652, is at 8.03pc with a T\text{eff} = 6450K and [Fe/H] = 0.03, corresponding to an F5V grid star. Two LW and three SW spectra were coadded and merged with a 6500K ATLAS spectrum.

τ Piscium, HD 222368, is at 13.79pc with a T\text{eff} = 6240K and [Fe/H] = -0.09, corresponding to an F7V grid star. Two LW and four SW spectra were coadded and merged with a 6250K ATLAS spectrum.

β Com, HD 114710, is at 9.15pc with a T\text{eff} = 5960K and [Fe/H] = 0.07, corresponding to an G0V grid star. Only one LW spectrum was correctable with the Massa routines and thus one LW and five SW spectra were coadded and merged with a 6000K ATLAS spectrum.

α Centauri A, HD 128620, is at 1.35 pc with a T\text{eff} = 5770K and [Fe/H] = 0.21, corresponding to a G2V grid star. Three LW and 93 SW spectra were coadded and merged with an upward shift of 1.25 to a 5750K ATLAS spectrum.

τ Ceti, HD 10700, is at 3.65pc with T\text{eff} = 5500K and [Fe/H] = -0.52, corresponding to a G8V grid star. Two LW and eight SW spectra were coadded and merged with a 5500K ATLAS spectrum.

HD 10780 is at 9.98pc with T\text{eff} = 5260K and [Fe/H] = 0.03, corresponding to a K0V grid star. It is a variable of the BY Draconis type. Five LW and four SW spectra were coadded and merged with a 5250K ATLAS spectrum.

ε Er i, HD 22049, is at 3.22pc with T\text{eff} = 5090K and [Fe/H] = -0.03, corresponding to a K2V grid star. ε Er i was chosen to compare with previous work (Segura et al., 2003; Grenfell et al., 2007; Selsis, 2000). ε Er i is a young star, only 0.7 Ga (Di Folco et al., 2004), and is thus more active than a typical K-dwarf. Due to its variability and close proximity there are frequent IUE observations. 17 LW and 72 SW IUE spectra were coadded and merged these with a 5000K ATLAS spectrum.

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\[ \text{We} \]

\[ \text{equivalent} \]

\[ \text{stellar} \]

\[ \text{models ranging from 7000K to 4250K in steps of 250K,} \]

\[ \text{coadded and merged to the 4250K} \]

\[ \text{BY Draconis type} \]

\[ \text{[Fe/H]} = -0.23, \text{corresponding to a K4V grid star. Seven LW and 30 SW IUE spectra were coadded and merged with a 4750K} \]

\[ \text{ATLAS} \]

\[ \text{61 Cyg A, HD 201091, is at 3.48 pc with} \]

\[ \text{Teff} = 4500K \] and \[ \text{[Fe/H]} = -0.43 \] (Cayrel de Strobel et al., 2001), corresponding to a K5V grid star. 61 Cyg A is a variable star of the BY Draconis type. Six LW and twelve SW spectra were coadded and merged with an upward shift of 1.15 to match the 4500K ATLAS spectrum.

\[ \text{BY Dra, HD 234677, is at 16.42 pc with} \]

\[ \text{Teff} = 4200K \] (Hartmann et al., 1977) and \[ \text{[Fe/H]} = 0 \] (Cayrel de Strobel et al., 1997), corresponding to a K7V grid star. It is a variable of the BY Draconis type. Eight LW and 30 SW spectra were coadded and merged to the 4250K ATLAS spectrum.

\[ \text{All input stellar spectra are shown in Fig. 3.} \]

### 2.4 Simulation Set-Up

To examine the effect of the SED of the host star on an Earth-like atmosphere, we build a temperature grid of stellar models ranging from 7000K to 4250K in steps of 250K, corresponding to F type stars to K dwarfs. We simulated an Earth-like planet with the same mass as Earth at the 1AU equivalent orbital distance, where the wavelength integrated stellar flux received on top of the planet’s atmosphere is equivalent to 1AU in our solar system, 1370 Wm^{-2}.

The biogeochemical fluxes were held fixed in the models in accordance with the fluxes that reproduce the modern mixing ratios in the Earth-Sun case (following Segura et al., 2003). We first calculate the surface fluxes for long-lived gases H2, CH4, N2O, CO and CH3Cl. Simulating the Earth around the Sun with 100 layers yields a \( T_{\text{surf}} = 288K \) for surface mixing ratios: \( c_{\text{H2}} = 5.5 \times 10^{-7} \), \( c_{\text{CH4}} = 1.6 \times 10^{-6} \), \( c_{\text{CO2}} = 3.5 \times 10^{-9} \), \( c_{\text{N2O}} = 3.0 \times 10^{-9} \), \( c_{\text{CO}} = 9.0 \times 10^{-8} \), and \( c_{\text{CH3Cl}} = 5.0 \times 10^{-10} \). The corresponding surface fluxes are -1.9 x 10^{12} g H2/year, 5.3 x 10^{14} g CH4/year, 7.9 x 10^{12} g N2O per year, 1.8 x 10^{15} g CO/year, and 4.3 x 10^{15} g CH3Cl/year. The best estimate for the modern CH4 flux is 5.35 x 10^{14} g/year (Houghton et al., 2004) and corresponds to the value derived in the model. Fluxes for the other biogenic species are poorly constrained. The N2 concentration is set by the total surface pressure of 1 bar. To explore the effect of UV and temperature separately, we combine a certain ATLAS model with varying UV files and vice versa.

### 3. Atmospheric Model Results and Discussion

The stellar spectrum has two effects on the atmosphere: first, the UV effect (§3.1) that primarily influences photochemistry and second, the temperature effect (§3.2) resulting from the difference in absorbed flux as a function of stellar SED. The same planet has a higher Bond albedo around hotter stars with SEDs peaking at shorter \( \lambda \), where Rayleigh scattering is more efficient, than around cooler stars, assuming the same total stellar flux (Snee & Ubachs, 2004). The overall result indicating planetary Bond albedo that includes both atmospheric as well as surface albedo is calculated by the climate/photochemistry model and varies between 0.13 – 0.22 for planets around F0 stars to K7 stars respectively because of the stars’ SED. Note that these values are lower than Earth’s planetary Bond albedo of 0.31 because the warming effect of clouds is folded into the albedo value in the climate code, decreasing it artificially.

#### 3.1 The influence of UV levels on Earth-like atmosphere models (UV effect)

To explore the effects of UV flux alone on the atmospheric abundance of different molecules, we combined specific IUE data files for stars with \( T_{\text{eff}} = 7000K, 6000K \) and 4500K (representing high, mid and low UV flux) with a fixed ATLAS photospheric models of \( T_{\text{eff}} = 6000K \). The temperature/pressure and chemical profiles of this test are shown in panels a) of Figs. 4 and 5. Hot stars provide high UV flux in the 2000 – 3200 Å range, e.g. a F0V grid star emits 130x more flux in this wavelength range than a K7V grid star (Figs. 1 and 2).

| \( T_{\text{eff}}(K) \) | Spectral Type Grid | Surface Temperature (K) | Ozone Column Depth (cm\(^{-2}\)) |
|----------------|-----------------|------------------------|-----------------------------|
| 7000           | F0V             | 279.9                  | 1.2 \times 10^{19}          |
| 6750           | F2V             | 281.7                  | 1.1 \times 10^{19}          |
| 6500           | F5V             | 283.2                  | 9.6 \times 10^{18}          |
| 6250           | F7V             | 284.6                  | 8.3 \times 10^{18}          |
| 6000           | F9V/G0V         | 286.4                  | 7.3 \times 10^{18}          |
| SUN            | G2V             | 288.1                  | 5.3 \times 10^{18}          |
| 5750           | G2V             | 287.7                  | 5.1 \times 10^{18}          |
| 5500           | G8V             | 289.1                  | 3.2 \times 10^{18}          |
| 5250           | K0V             | 290.9                  | 4.1 \times 10^{18}          |
| 5000           | K2V             | 291.9                  | 3.3 \times 10^{18}          |
| 4750           | K4V             | 292.8                  | 2.6 \times 10^{18}          |
| 4500           | K5V             | 297.0                  | 2.6 \times 10^{18}          |
| 4250           | K7V             | 300.0                  | 3.5 \times 10^{18}          |

Table 2: Surface temperature and O3 column depth for an Earth-like planet model orbiting the grid stars.

The Chapman reactions are driven primarily by photolysis in this wavelength range and the atmosphere models show an according increase in O3 concentration and subsequent strong temperature inversion for planets orbiting hot grid stars (Table 2). The maximum heating in the stratosphere is a few
3.2 The influence of stellar T\textsubscript{eff} on Earth-like atmosphere models (Temperature effect)

To explore the effects of stellar T\textsubscript{eff} alone on the atmospheric abundance of different molecules, we combined specific photospheric ATLAS spectrum of T\textsubscript{eff} = 7000K, 6000K and 4500K (representing high, mid and low stellar T\textsubscript{eff}) with a fixed UV data file of T\textsubscript{eff} = 6000K. The temperature/pressure and chemical profiles of this test are shown in panels b) of Figs. 4 and 5. T\textsubscript{eff} affects H\textsubscript{2}O vapor concentrations due to increased evaporation for high planetary surface temperature which is transported to the stratosphere. Fig. 4 shows an overall increase in tropopause and stratosopause height for low stellar T\textsubscript{eff} with according hot planetary surface temperatures.

The response of O\textsubscript{3} to stellar T\textsubscript{eff} is weak due to two opposing effects: high stellar T\textsubscript{eff} and according low planetary surface and atmospheric temperatures increase O\textsubscript{3} concentration by slowing Chapman reactions that destroy O\textsubscript{3}, but also increase NO\textsubscript{x}, HO\textsubscript{3}, and ClO\textsubscript{3} concentrations which are the primary sinks of O\textsubscript{3} (see also Grenfell et al., 2007).

Both CH\textsubscript{4} and CH\textsubscript{3}Cl show only a weak temperature dependence. The rate of the primary reactions of CH\textsubscript{4} and CH\textsubscript{3}Cl with OH slows with decreasing temperature, causing an increase in CH\textsubscript{4} and CH\textsubscript{3}Cl for lower planetary surface temperatures. N\textsubscript{2}O displays a similar weak temperature effect.

All of our simulations used a fixed mixing ratio of 355ppm for CO\textsubscript{2} and 21% O\textsubscript{2}. Since both O\textsubscript{3} and CO\textsubscript{2} are well mixed in the atmosphere, their vertical mixing ratio profiles are not shown.

3.3 The influence of stellar SED on Earth-like atmosphere models

Figs. 6 and 7 show the combined temperature and UV effect on Earth-like atmospheres. The surface temperature of an Earth-like planet increases with decreasing stellar effective temperature due to decreasing reflected stellar radiation and increasing IR absorption by H\textsubscript{2}O and CO\textsubscript{2} (see Table 2 and Fig. 6). The late K-dwarf stars show in addition a near isothermal stratosphere.

Figures 4 and 5 show the combined temperature and UV effect. Figure 4 illustrates temperature/altitude profiles for several unphysical test where we: a) combine high, mid, and low UV fluxes (IUE observations for stars with T\textsubscript{eff} = 7000K, 6000K, and 4500K, respectively) with a fixed ATLAS photosphere model for T\textsubscript{eff} = 6000K to show the “UV effect”, and b) combine high, mid, and low stellar photosphere models (ATLAS models for T\textsubscript{eff} = 7000K, 6000K, and 4500K, respectively) with a fixed UV flux for T\textsubscript{eff} = 6000K to show the “Temperature effect”.

Figures 5 show the chemical mixing ratio profiles for H\textsubscript{2}O, O\textsubscript{3}, CH\textsubscript{4}, and N\textsubscript{2}O from several unphysical test where we: a) combine high, mid, and low UV fluxes (IUE observations for stars with T\textsubscript{eff} = 7000K, 6000K, and 4500K, respectively) with a fixed ATLAS photosphere model for T\textsubscript{eff} = 6000K to show the “UV effect”, and b) combine high, mid, and low stellar photosphere models (ATLAS models for T\textsubscript{eff} = 7000K, 6000K, and 4500K, respectively) with a fixed UV flux for T\textsubscript{eff} = 6000K to show the “Temperature effect”.

kilometers above the peak of the O\textsubscript{3} concentration where both a high enough concentration of O\textsubscript{3} and a high enough flux of photons is present. O\textsubscript{3} abundance increases OH abundance, the primary sink of CH\textsubscript{4} and CH\textsubscript{3}Cl. Figs. 5 and 7 show a corresponding decrease in those molecules for high UV environment. O\textsubscript{3} shields H\textsubscript{2}O in the troposphere from UV environments. Stratospheric H\textsubscript{2}O is photolyzed by λ < 2000 Å or reacts with excited oxygen, O'\textsubscript{3}D to produce OH radicals. Accordingly stratospheric H\textsubscript{2}O concentration decreases with decreasing UV flux. N\textsubscript{2}O decreases with increasing UV flux because of photolysis by λ < 2200 Å. N\textsubscript{2}O is also an indirect sink for stratospheric O\textsubscript{3} when it is converted to NO. Therefore decreasing N\textsubscript{2}O increases O\textsubscript{3} abundance. O\textsubscript{2} and CO\textsubscript{2} concentrations remain constant and well mixed for all stellar types.
planetary surface temperatures, and therefore high amounts of surface temperature of the planet. Earth flux UV temperature and concentration at atmosphere, will be modeled in a future paper. et al., grid stars emit low UV flux and therefore produce near However, in the 2000 cold grid star, $T_{\text{eff}}(4250\text{K})$ show increased stratosphere $H_2O$ concentration through increased vertical transport in the nearly isothermal stratospheres as well as production by stratospheric $\text{CH}_4$ (see e.g. Segura et al. 2005 for similar behavior in planets around M-dwarfs). In particular, the atmosphere models for a planet around $T_{\text{eff}} = 4250\text{K}$ grid star has a high OH concentration in the stratosphere due to increased $O_3$ and $H_2O$ at those altitudes.

$N_2O$ is primarily produced by denitrifying bacteria and has increased linearly due to agriculture since the preindustrial era at a rate of around 0.26% yr$^{-1}$ (Forster et al., 2007). Up to about 20km, there is no significant difference between stellar types in $N_2O$ concentration. Above ~20km, Fig. 7 shows a decrease in $N_2O$ concentration for atmosphere models around hot compared to cool grid stars since UV is the primary sink of $N_2O$ in the stratosphere. Below 20km $N_2O$ is shielded from photolysis by the $O_3$ layer. Note that the general trend for increasing $N_2O$ for colder grid stars reverses for our coldest grid star. This is due to the increased UV flux which destroys $N_2O$ and an increase in $O_3$ which causes an increase in $O(^{1}\text{D})$, another strong sink for $N_2O$.

$\text{CH}_3\text{Cl}$ concentration decreases with increased stellar UV flux since OH which act as sink for $\text{CH}_3\text{Cl}$.

4. RESULTS: SPECTRA OF EARTH-LIKE PLANETS ORBITING F0V TO K7V GRID STARS

We include both a clear sky as well as a 60% global cloud cover spectrum which has cloud layers analogous to Earth (40% 1km, 40% 6km and 20% 12km following Kaltenegger et al., 2007) in Figs. 8–11 to show the importance of clouds on the reflected and emission planet spectra. We present the spectra as specific flux at the top of the atmosphere of Earth-like planets. In the VIS, the depth of the absorption features is primarily sensitive to the abundance of the species, while in the IR, both the abundance and the temperature difference between the emitting/absorbing layer and the continuum influences the depth of features.

We use a Lambert sphere as an approximation for the disk integrated planet in our model. The surface of our model planet corresponds to Earth’s current surface of 70% ocean, 2% coast, and 28% land. The land surface consists of 30% grass, 30% trees, 9% granite, 9% basalt, 15% snow, and 7% sand. Surface reflectivities are taken from the USGS Digital Spectral Library$^2$ and the ASTER Spectral Library$^3$ (following Kaltenegger et al., 2007). Note the vegetation red edge feature at 0.76 µm is only detectable in the clear sky model spectra in low resolution, see Fig. 8 (see e.g Kaltenegger et al. 2007, Seager et al. 2002, Palle et al. 2008). No noise has been added to these model spectra to provide input models for a wide variety of instrument simulators for both secondary eclipse and direct detection simulations.

We assume full phase (secondary eclipse) for all spectra presented to show the maximum flux that can be observed.

\hspace{1cm}$^2$ http://speclab.cr.usgs.gov/spectral-lib.html
\hspace{1cm}$^3$ http://speclib.jpl.nasa.gov
Figure 8: Smoothed, disk-integrated VIS/NIR spectra at the top of the atmosphere (TOA) for an Earth-like planet around FGK stars for both a clear sky (left) and 60% cloud coverage (right) model (region 2-4 $\mu$m has low integrated flux levels and therefore is not shown here).

Figure 9: Individual features of O$_3$ at 0.6 $\mu$m, O$_2$ and 0.76 $\mu$m, H$_2$O at 0.95 $\mu$m, and CH$_4$ at 1.7$\mu$m for F0V – K7V grid stars (left) planet-to-star contrast ratio and absolute flux levels (middle) for a clear sky and (right) 60% cloud coverage model. Note the different y-axes. Legend and color coding are the same in figures 6 to 11.
Figure 10: Smoothed, disk-integrated IR spectra at the top of the atmosphere (TOA) for Earth-like planets around F0V to K7V grid stars for both a clear sky (left) and 60% cloud coverage (right) model.

Figure 11: Individual features of O\(_3\) at 9.6 \(\mu m\), CO\(_2\) and 15 \(\mu m\), H\(_2\)O at 5-8 \(\mu m\), and CH\(_4\) at 7.7\(\mu m\) for F0V – K7V grid stars (left) planet-to-star contrast ratio and absolute flux levels (middle) for a clear sky and (right) 60% cloud coverage model. Legend and color coding are the same in figures 2 to 8.
Note that we use an Earth-size planet to determine the specific flux and planet-to-star contrast ratio. A Super-Earth with up to twice Earth’s radius will provide 4 times more flux and a better contrast ratio than shown in Figs. 8 to 14.

4.1 Earth-like Visible/Near-infrared Spectra (0.4µm – 4µm)

Fig. 8 shows spectra from 0.4 to 2µm of Earth-like planets for both a clear-sky and Earth-analogue cloud cover for the grid stars (F0V-K7V). The high resolution spectra have been smoothed to a resolving power of 200 using a triangular smoothing kernel. Figs. 8 and 9 show that clouds increase the reflectivity of an Earth-like planet in the VIS to NIR substantially and therefore overall increase the equivalent width of all observable feature, even though they block access to some of the lower atmosphere.

Fig. 9 shows individual features for the strongest atmospheric features from 0.4 to 4µm for Earth-like planets orbiting the grid stars: O3 at 0.6 µm (the Chappuis band), O2 and 0.76 µm, H2O at 0.95 µm, and CH4 at 1.7µm. The left panel of each row shows the relative flux as planet-to-star contrast ratio, the middle and right panel show the specific, top-of-atmosphere flux for a clear and 60% cloud cover, respectively. From the planet-to-star contrast ratios in Figs. 9, 11 and 13 the photometric precision required to detect these features for Earth-like planets can be calculated. Note that any shallow spectral features like the visible O3 feature would require a very high SNR to be detected.

The 0.6 µm shallow O3 spectral feature depth increases with Teff of the star host since O3 concentration increases with UV levels but is difficult to distinguish from Rayleigh scattering. The relative depth of the O2 feature at 0.76 µm is constant but the flux decreases for cool grid stars due to the decrease in absolute stellar flux received and reflected by the planet at short wavelengths. The depth of the H2O absorption feature at 0.9 µm (shown) 0.8, 1.1 and 1.4 µm increase for planets orbiting cool grid stars due to their increased H2O abundance. The depth of the CH4 absorption feature at 1.7µm increases with decreasing stellar Teff due to the increase of CH4 abundance.

From 2 to 4 µm there are CH4 features at 2.3µm and 3.3 µm, a CO2 feature at 2.7µm, and H2O absorption at 2.7µm and 3.7µm. However, due to the low emergent flux in this region, these features are not shown individually.

4.2 Earth-like Infrared Spectra, IR (4µm – 20µm)

Fig. 10 shows spectra from 4 to 20µm of Earth-like planets for both a clear sky and Earth-analogue cloud cover for the grid stars (F0V-K7V). The high resolution spectra have been smoothed to a resolving power of 250 using a triangular smoothing kernel. Clouds decrease the overall emitted flux of an Earth-like planet in the IR.

Fig. 11 shows individual features for the strongest atmospheric features from 4 to 20µm for Earth-like planets orbiting the grid stars: O3 at 9.6µm, CO2 at 15 µm, H2O at 6.3µm and CH4 at 7.7µm for a cloud free and Earth-analogue cloud coverage model. The left panel of each row shows the relative flux as planet-to-star contrast ratio, the middle and right panel show the specific, top-of-atmosphere flux for a clear and 60% cloud coverage case, respectively.

In the clear sky model, the depth of the O3 feature at 9.6µm decreases for planet models orbiting hot grid stars, despite increasing O3 abundance, due to lower contrast between the continuum and absorption layer temperature. For Earth-analogue cloud cover, however, O3 is seen in emission for Teff ≥ 6500K due to the lower continuum temperature.

Due to the hot stratosphere for all grid stars with Teff > 6000K, the CO2 absorption feature at 15 µm has a prominent central emission peak. Clouds reduce the continuum level and the depth of the observable CO2 feature.

The CH4 feature at 7.7µm is prominent in the planetary spectra around cool grid stars due to high CH4 abundance in low UV environments. The CH4 feature is also partially obscured by the wings of the H2O feature at 5-8µm. The depth of the H2O features at 5-8 and 18+ µm do not change significantly even though H2O abundance increases for cool grid stars. Clouds reduce the continuum level and the depth of the observable H2O features.

Fig. 13 shows planet-to-star contrast ratio for Earth-analogue cloud coverage of an Earth-like planet from which the photometric precision required can be calculated. The planet-to-star contrast ratio is between 10⁻⁸ to 10⁻¹¹ in the VIS/NIR and between about 10⁻⁶ and 10⁻¹⁰ in the IR for the grid stars. For the whole wavelength range, the contrast ratio improves for cool grid stars.

![Figure 12: Spectra of Earth-like planets for 100% cloud coverage at 3 cloud heights (1km, 6km and 12km, blue, red and black line, respectively) as well as clear sky spectrum (dashed line) from 0.4 to 20 µm, orbiting a T eff = 7000K (top) T eff = 5750K (middle), and T eff = 4250K (bottom) grid star for comparison.](image)

4.3 The effect of clouds on an Earth-like planet spectra from 0.4 to 20µm

Fig. 12 shows Earth-like planet spectra for 100% cloud cover at 1km, 6km and 12km from 0.4 to 20µm for three sample grid stars with Teff = 7000K (top), 5750K (middle), and 4250K (bottom). The clear sky spectrum is shown as dashed line for comparison. Clouds increase the reflectivity of an Earth-like planet in the VIS to NIR substantially and therefore overall increase the equivalent width of all observable features, even though they block access to some of the lower atmosphere. Clouds decrease the overall emitted flux of an Earth-like planet in the IR slightly because they radiate at lower temperatures and therefore overall decrease the equivalent width of all observable features.
absorption features, even though they can increase the relative
depth of a spectral feature due to lowering the continuum
temperature of the planet.

N₂O and CH₃Cl have features from the NIR to IR (see Fig. 14)
but in modern Earth concentrations do not have a strong enough
feature to be detected with low resolution. For the clear sky
models, the vegetation red edge is detectable due to the order of
magnitude increased reflectance from 0.7 μm to 0.75 μm for all
grid stars. Clouds obscure that feature (see Fig. 8).

For detecting an oxidizing gas in combination with a reducing
gas in Earth-like planet atmosphere models, the coolest grid stars
in our sample are the best targets. In this paper we have not
modeled planets orbiting stars cooler than ~4000K to provide a
consistent set of planetary models. As discussed in Segura et al.
2005, cool host stars with low UV flux, provide an environment
that leads to run-away CH₄ accumulation in the atmosphere and
therefore the model for Earth-like planets around M-dwarfs
often use abiologic CH₄ levels, not consistent with Earth-analogue
models used in this study. We will explore this effect in a future
work.

No noise has been added to these model spectra to provide
input models for a wide variety of instrument simulators for both
secondary eclipse and direct detection simulations. Different
instrument simulators for JWST (see e.g Deming et al., 2009,
Kaltenegger & Traub 2009) explore the capability of JWST’s
MIRI and NIRspec Instrument to characterize extrasolar planets
down to Earth-like planets, with interesting results for planets
around close-by as well as luminous host stars. Several new
results are forthcoming by several groups that will provide
realistic instrument parameters that can be used to determine
detectability of these absorption features. Future ground and
space based telescopes are being designed to characterize
exoplanets down to Earth-like planets and will provide
interesting opportunities to observe atmospheric features,
especially for Super-Earths, with radii up to 2 time Earth’s
radius and therefore 4 times the flux and planet-to-star contrast
ratio levels quoted for Earth-size planets shown in Figs. 8-14.

5. DISCUSSION

When choosing IUE stars to for our stellar spectral grid, we
avoided stars of unusual variability, but did not exclude stars that
had representative variability of its stellar class. Several of our
representative K stars are variables of the BY Draconis type
which is a common variable in this stellar type. We
preferentially choose stars with near solar metallicity when
possible; however, the IUE database does not provide candidate
stars at each temperature of solar metallicity. Several stars have
lower than solar metallicity. We compared a subsolar stellar
metallicity with a solar metallicity spectra model and found that
the difference does not impact our results.

**Observability of Biosignatures:** Detecting the combination of
O₂ or O₃ and CH₄ for emergent spectra and secondary eclipse
measurements requires observations in the IR or in the VIS/NIR
up to 3 μm to include the 2.4 μm CH₄ feature in that spectral
range. The strength of the absorption features depend on the
stellar effective temperature of the host star and vary
significantly between stellar types. In the IR, CH₄ at 7.7 μm is
more detectable at low resolution for cool grid stars than hot grid
stars. The 9.6 μm O₃ feature is deepest for mid to cool stars and
becomes less detectable for hotter stars. However around our
hottest grid stars, the 9.6 μm O₃ feature becomes an apparent
emission feature for cloudy atmospheres. The narrow O₃ feature
in the VIS at 0.72 μm is of comparable strength for all grid stars.
H₂O has strong features for all grid stars over the whole
wavelength range.
In addition to the size of the planet, future observations will occur at different positions throughout the planet’s orbit. The maximum observable planetary flux in the visible scales with the illuminated fraction of the planet, that is “visible” to the observer. In the IR the maximum flux remains constant throughout the planet’s orbit, assuming a similar temperature on the day and night side. In Fig. 15 we show the absolute specific flux levels at full phase, gibbous phase, and quadrature (phase angles of 0°, 45°, and 90°, respectively) for 60% cloud coverage Earth-like planets orbiting three grid stars with T\text{eff} = 7000K, 5750K and 4250K to show the effect of orbital position (see also Robinson et al., 2011). We scaled our full-phase simulations to other phases using a Lambert phase function. For quadrature, representing an average viewing geometry, the contrast ratios presented in Fig. 13 will be a factor of ~2 lower in the visible. Assuming the planet has efficient heat transport from the day to night side, the specific flux levels and contrast ratios in the IR will be unchanged.

**6. CONCLUSIONS**

We calculated the spectra for terrestrial atmosphere models receiving the same incoming flux as Earth when orbiting a grid of host stars with T\text{eff} = 4250K to T\text{eff} = 7000K in 250K increments, comprehensively covering the full FGK stellar range. We discuss the spectral features for clear and cloudy atmosphere models and compare the effect of the stars SED and UV flux on both the atmospheric composition as well as the detectable atmospheric features in section 3 and 4. Increasing UV environments (generally coupled with increasing stellar T\text{eff} for main sequence stars) result in: increasing concentration of O3 from photolysis, increasing stratospheric H2O from O3 shielding, increasing OH based on increased O3 and H2O concentrations, and decreasing CH4, CH3Cl, and N2O from photolysis and reactions with OH. Increasing stellar temperatures and corresponding decreasing planetary surface temperatures result in: decreasing tropospheric H2O due to decreased temperatures, decreasing stratospheric H2O from transport, and decreasing reaction rates of OH with CH4, N2O and CH3Cl. The overall effect as the stellar effective temperature of the main sequence grid stars increases, is an increase in O3 and OH concentration, a decrease in tropospheric H2O (but an increase stratospheric H2O), and a decrease in stratospheric CH4, N2O, CH3Cl.

In the infrared, the temperature contrast between the surface and the continuum layer is strongly impacts the depth of spectral features. While O3 increases for hotter main sequence stars the strength of the 9.6µm band decreases due to the decrease temperature difference between the continuum and the emitting layer. For hot stars, with T\text{eff} ≥ 6750K the O3 feature appears as emission due to the contrast to the continuum.

Our results provides a grid of atmospheric compositions as well as model spectra from the VIS to the IR for JWST and other future direct detection mission design concepts. The model spectra in this paper are available at www.cfa.harvard.edu/~srugheimer/FGKspectra/.

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Figure 14: Relative absorption of individual chemical species H$_2$O, CO$_2$, O$_2$, O$_3$, CH$_4$, N$_2$O and CH$_3$Cl for three sample grid stars with T$_{\text{eff}}$ = 7000K, 5750K, and 4250K.
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