Spectral Fingerprints of Earth-like Planets Around FGK Stars

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Spectral Fingerprints of Earth-like Planets Around FGK Stars

Sarah Rugheimer,1 Lisa Kaltenegger,1,2 Andras Zsom,2,3 Antigona Segura,4 and Dimitar Sasselov1

Abstract

We present model atmospheres for an Earth-like planet orbiting the entire grid of main sequence FGK stars with effective temperatures ranging from $T_{\text{eff}} = 4250$ K to $T_{\text{eff}} = 7000$ K in 250 K intervals. We have modeled the remotely detectable spectra of Earth-like planets for clear and cloudy atmospheres at the 1 AU equivalent distance from the VIS to IR (0.4 to 20 $\mu$m) to compare detectability of features in different wavelength ranges in accordance with the James Webb Space Telescope and future design concepts to characterize exo-Earths. We have also explored 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, H$_2$O, O$_3$, CH$_4$, N$_2$O, and CH$_3$Cl.

The increase in UV dominates changes of O$_3$, OH, CH$_4$, N$_2$O, and CH$_3$Cl, whereas the increase in stellar temperature dominates changes in H$_2$O. 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 atmosphere models show more O$_3$ and OH but less stratospheric CH$_4$, N$_2$O, CH$_3$Cl, and tropospheric H$_2$O (but more stratospheric H$_2$O) with increasing effective temperature of main sequence stars. The corresponding detectable spectral features, on the other hand, show different detectability depending on the wavelength observed.

We concentrate on directly imaged planets here as a framework to interpret future light curves, direct imaging, and secondary eclipse measurements of atmospheres of terrestrial planets in the habitable zone 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., Udry et al., 2007; Borucki et al., 2011; Kaltenegger and Sasselov, 2011; Batalha et al., 2012) with masses and radii consistent with rocky planet models. Recent radial velocity results as well as Kepler observations demonstrate that small planets in the habitable zone 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 Webb 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., 2011a, 2011b). In the present study, we expanded on this work by establishing planetary atmosphere models for the full FGK main sequence, using a stellar temperature grid from 7000 to 4250 K, in increments of 250 K, 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 to 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 Earth’s 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 by-products of life processes. In our analysis, we focused particularly on spectral features of chemical species that indicate habitability for a temperate rocky planet like Earth, H2O, O2, CH4, N2O, and CH3Cl (Lovelock, 1975; Sagan et al., 1993).

In Section 1, we introduce the photochemistry of an Earth-like atmosphere. In Section 2, we describe our model for calculating the stellar spectra, atmospheric models, and planetary spectra. Section 3 presents the influence of stellar types on the abundance of various atmospheric chemical species. In Section 4, we examine the remote observability of such spectral features, and in Sections 5 and 6, we conclude by summarizing the results and discussing their implications.

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 O2/O3 with CH4/N2O, and CH3Cl. Note that one spectral feature, for example, O2 does not constitute a biosignature by itself, as the planetary context (like bulk planet, atmospheric composition, and planet insolation) must be taken into account to interpret this signature. Detecting high concentrations of a reducing gas concurrently with O2 or O3 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, O3 can be used as a proxy for oxygen at 10^{-5} present atmospheric level of O2; the depth of the 9.6 μm O3 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 μm O3 feature’s nonlinear dependence on the O2 concentration, observing in the VIS at 0.76 μm would be a more accurate O2 level indicator but requires higher resolution than detecting O3.

N2O and CH3Cl 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 H2O or CO2 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., 2002; Meadows, 2006; Kaltenegger et al., 2010a) for a more in-depth discussion on habitability and biosignatures. In this section, we briefly discuss the most important photochemical reactions involving H2O, O2, O3, CH4, N2O, and CH3Cl.

**Water, H2O:** Water vapor is an important greenhouse gas in Earth’s atmosphere. Over 99% of H2O vapor is currently in the troposphere, where it is an important source of OH via the following set of reactions:

\[
\text{O}_3 + h\nu \rightarrow \text{O}_2 + \text{O}(^1\text{D}) \quad (R1)
\]

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

In the troposphere, the production of O(^1D) takes place for 3000 Å < \lambda < 3200 Å, the lower limit of which is set by the inability of wavelengths, \lambda, shorter than 3000 Å to reach the troposphere due to O3 shielding. H2O, 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 3000 Å is very low. Stratospheric H2O can be transported from the troposphere or formed in the stratosphere by CH4 and OH.

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

**Oxygen and ozone, O2 and O3:** In an atmosphere containing O2, O3 concentrations are determined by the absorption of UV light shortward of 2400 Å in the stratosphere. O3 is an oxidizing agent more reactive than O2, the most stable form of oxygen, due to the third oxygen atom being loosely bound by a single bond. O3 is also an indirect measure of OH since reactions involving O3 and H2O are sources of OH. OH is very reactive and is the main sink for reducing species such as CH4. O3 is formed primarily by the Chapman reactions (1930) of the photolysis of O2 by UV photons (1850 Å < \lambda < 2420 Å) and then the combining of O2 with O.

\[
\text{O}_2 + h\nu \rightarrow \text{O} + \text{O} (\lambda < 240 \text{ nm}) \quad (R4)
\]

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

\[
\text{O}_3 + h\nu \rightarrow \text{O}_2 + \text{O} (\lambda < 320 \text{ nm}) \quad (R6)
\]

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

where M is any background molecule such as O2 or N2. 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 O3 by a factor of 2 on Earth. Hydrogen oxide (HOx), nitrogen oxide (NOx), and chlorine (ClOx) radicals are the additional sinks controlling the O3 abundance (Bates and Nicolet, 1950; Crutzen, 1970; Molina and Rowland, 1974, respectively), with NOx and HOx, being the dominant and second-most-dominant sinks, respectively.
Methane, CH4: Since CH4 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., 1994). In both the troposphere and stratosphere, CH4 is oxidized by OH, which is the largest sink of the global methane budget. In the stratosphere, CH4 is also destroyed by UV radiation. Though its photodissociation energy is 2722 Å, its absorption cross section is not sufficient for $\lambda > 1500$ Å. CH4 is produced biotically by methanogens and termites and abiotically through hydrothermal vent systems. In the modern atmosphere, there is a significant anthropogenic source of CH4 from natural gas, livestock, and rice paddies. CH4 is 25× more effective as a greenhouse gas than CO2 in modern Earth’s atmosphere (Forster et al., 2007) and may have been much more abundant in early Earth (see, e.g., Pavlov et al., 2003).

Nitrous oxide, N₂O: N₂O 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 O3, and 95% produces N₂.

$$N_2O + O(^1D) \rightarrow 2NO$$ (R8)

On current Earth, N₂O is emitted primarily by denitrifying bacteria with anthropogenic sources from fertilizers in agriculture, biomass burning, industry, and livestock.

Methyl chloride, CH₃Cl: CH₃Cl 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 CH₃Cl in Earth’s atmosphere is by OH as seen in R9, but it can also be photolyzed or react with atomic chlorine. Because CH₃Cl is a source of chlorine in the stratosphere, it also plays a role in the removal of O₃ as discussed earlier.

$$CH_3Cl + OH \rightarrow Cl + H_2O$$ (R9)

$$CH_3Cl + h\nu \rightarrow CH_3 + Cl$$ (R10)

$$CH_3Cl + Cl \rightarrow HCl + Cl$$ (R11)

2. Model Description

We use EXO-P (Kaltenegger and Sasselov 2010), a coupled one-dimensional radiative transfer atmosphere code developed for rocky exoplanets based on a 1-D climate (Kasting and Ackerman, 1986; Pavlov et al., 2000; Haqq-Misra et al., 2008), 1-D photochemistry (Pavlov and Kasting, 2002; Segura et al., 2005, 2007), and 1-D radiative transfer model (Traub and Stier, 1976; Kaltenegger and 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 1-D global atmosphere model profile is generated by using a plane parallel atmosphere, treating the planet as a Lambertian sphere, and setting the stellar zenith angle to 60° to represent the average incoming stellar flux on the dayside of the planet (see also Schindler and Kasting, 2000). 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 VIS/near IR to calculate the shortwave fluxes. Four-term, correlated-k coefficients parameterize the absorption by O₃, H₂O, O₂, and CH₄ in wavelength intervals shown in Fig. 1 (Pavlov et al., 2000). In the thermal IR region, a rapid radiative transfer model 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 288 K (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 with 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 and Stier, 1976) and further developed for exoplanet transmission and emergent spectra (Kaltenegger et al., 2007; Kaltenegger and Traub, 2009; Kaltenegger et al., 2010; Kaltenegger and Sasselov, 2010, 2011). In this paper, we model Earth’s reflected and thermal emission spectra, using 21 of the most spectrscopically significant molecules (H₂O, O₃, O₂, CH₄, CO₂, OH, CH₃Cl, NO₂, N₂O, HNO₃, CO, H₂S, SO₂, H₂O₂, NO, CIO, HOCI, HO₂, H₂CO, N₂O₅, and HCl).

With 34 layers, the spectrum is calculated at high spectral resolution, with several points per line width, where the line shapes and widths are computed by 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 wave-number steps. The figures are shown smoothed to a resolving power of 250 in the IR and 800 in the VIS with a triangular smoothing kernel. The spectra may further be binned corresponding to proposed future spectroscopy mission designs to characterize Earth-like planets.

2.2. Model validation with EPOXI

We previously validated EXO-P from the VIS to the IR with data from ground and space (Kaltenegger et al., 2007). Here, we use new data by EPOXI in the VIS and near IR (Livengood et al., 2011) for further validation (see Fig. 2). The data set we use to validate our VIS and the near-IR Earth model spectra is the first EPOXI observation of Earth, which was averaged over 24 h on 03/18/2008–03/19/2008 and taken at a phase angle of 57.7°. Atmospheric models found the best match to be for a 50% cloud coverage with 1.5 km and 8.5 km cloud layer, respectively (Robinson et al., 2011).
Here, we use a 60% global cloud cover spectrum divided between three layers: 40% water clouds at 1 km, 40% water clouds at 6 km, and 20% ice clouds at 12 km (following Kaltenegger et al., 2007), consistent with an averaged Earth profile to compare our model to this 24h 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 VIS are at 0.45 and 0.95 μm (with an 8% and 18% error, respectively).
2.3. Stellar spectral grid model

The stellar spectral grid ranges from 4250 to 7000 K in effective temperature increments of 250 K. 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.1 We use IUE measurements to extend ATLAS synthetic spectra to generate input spectra files from 1150 to 45,450 Å (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.

The IUE satellite had three main cameras, the longwave (LWP/LWR) cameras (1850–3350 Å) and the shortwave (SW) camera (1150–1975 Å). When preparing the IUE data (following Massa et al., 1998; Massa and Fitzpatrick, 2000; Segura et al., 2003), we used a sigma-weighted average to coadd the multiple SW and LW observations. We used a linear interpolation when there were 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 NSSED [derived from Flower (1996) and Valenti and Fischer (2005), respectively] unless otherwise cited. See Table 1 for a summary list of the representative IUE stars.

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HD 40136, η Lep, is at 15.04 pc with $T_{\text{eff}}=7060$ K 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 7000 K ATLAS spectrum.

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

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

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

β Com, HD 114710, is at 9.15 pc with $T_{\text{eff}}=5960$ K and [Fe/H] = 0.07, corresponding to a 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 6000 K ATLAS spectrum.

α Centauri A, HD 128620, is at 1.35 pc with $T_{\text{eff}}=5770$ K 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 5750 K ATLAS spectrum.

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

HD 10780 is at 9.98 pc with $T_{\text{eff}}=5260$ K 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 5250 K ATLAS spectrum.

ε Eridani, HD 22049, is at 3.22 pc with $T_{\text{eff}}=5090$ K and [Fe/H] = −0.03, corresponding to a K2V grid star. ε Eri was chosen to compare with previous work (Selsis, 2000; Segura et al., 2003; Grenfell et al., 2007). ε Eri 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 with a 5000 K ATLAS spectrum.

ε Indi, HD 209100, is at 3.63 pc with $T_{\text{eff}}=4730$ K and [Fe/H] = −0.23, corresponding to a K4V grid star. Seven LW and 30 SW IUE spectra were coadded and merged with a 4750 K ATLAS spectrum.

61 Cyg A, HD 201091, is at 3.48 pc with $T_{\text{eff}}=4500$ K and [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 12 SW spectra were coadded and merged with an upward shift of 1.15 to match the 4500 K ATLAS spectrum.

BY Dra, HD 234677, is at 16.42 pc with $T_{\text{eff}}=4200$ K (Hartmann and Anderson, 1977) and [Fe/H] = 0.0 (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 4250 K ATLAS spectrum.

All input stellar spectra are shown in Fig. 3.

2.4. Simulation setup

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

The biogenic 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 H\(_2\), CH\(_4\), N\(_2\)O, CO, and CH\(_3\)Cl. Simulating Earth around the Sun with 100 layers yields \(T_{\text{surf}}=288\) K for surface mixing ratios: \(c_{\text{H}_2}=5.5 \times 10^{-7}\), \(c_{\text{CH}_4}=1.6 \times 10^{-6}\), \(c_{\text{CO}_2}=3.5 \times 10^{-4}\), \(c_{\text{N}_2\text{O}}=3.0 \times 10^{-7}\), \(c_{\text{CO}}=9.0 \times 10^{-8}\), and \(c_{\text{CH}_3\text{Cl}}=5.0 \times 10^{-10}\). The corresponding surface fluxes are \(-1.9 \times 10^{12}\) g H\(_2\)/year, \(5.3 \times 10^{14}\) g CH\(_4\)/year, \(7.9 \times 10^{12}\) g N\(_2\)O per year, \(1.8 \times 10^{15}\) g CO/year, and \(4.3 \times 10^{12}\) g CH\(_3\)Cl/year. The best estimate for the modern CH\(_4\) flux is \(5.35 \times 10^{14}\) g/year (Houghton et al., 1994) and corresponds to the value derived in the model. Fluxes for the other biogenic species are poorly constrained. The N\(_2\)O 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. Effect of Stellar SED on Atmospheric Models

The stellar spectrum has two effects on the atmosphere: first, the UV effect (Section 3.1) that primarily influences photochemistry and second, the temperature effect (Section 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 it would have around cooler stars, assuming the same total stellar flux (Sneep and Ubachs, 2004). The overall resulting planetary Bond albedo that includes both atmospheric as well as surface albedo is calculated by the climate/photochemistry model and varies between 0.13 and 0.22 for planets around

### Table 2. Surface Temperature and O\(_3\) Column Depth for an Earth-like Planet Model Orbiting the Grid Stars

<table>
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<tr>
<th>T(_{\text{eff}}) (K)</th>
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<th>Ozone column depth (cm(^{-2}))</th>
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<tr>
<td>7000</td>
<td>F0V</td>
<td>279.9</td>
<td>(1.2 \times 10^{19})</td>
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<tr>
<td>6750</td>
<td>F2V</td>
<td>281.7</td>
<td>(1.1 \times 10^{19})</td>
</tr>
<tr>
<td>6500</td>
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<td>5000</td>
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<td>4250</td>
<td>K7V</td>
<td>300.0</td>
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</table>
FIG. 4. Temperature/altitude profiles for several unphysical tests where we (a) combine high, mid, and low UV fluxes (IUE observations for stars with $T_{\text{eff}} = 7000$, 6000, and 4500 K, respectively) with a fixed ATLAS photosphere model for $T_{\text{eff}} = 6000$ K to show the “UV effect” and (b) combine high, mid, and low stellar photosphere models (ATLAS models for $T_{\text{eff}} = 7000$, 6000, and 4500 K, respectively) with a fixed UV flux for $T_{\text{eff}} = 6000$ K to show the “temperature effect.” (Color graphics available online at www.liebertonline.com/ast)

FIG. 5. Chemical mixing ratio profiles for H$_2$O, O$_3$, CH$_4$, and N$_2$O from several unphysical tests where we (a) combine high, mid, and low UV fluxes (IUE observations for stars with $T_{\text{eff}} = 7000$, 6000, and 4500 K, respectively) with a fixed ATLAS photosphere model for $T_{\text{eff}} = 6000$ K to show the “UV effect” and (b) combine high, mid, and low stellar photosphere models (ATLAS models for $T_{\text{eff}} = 7000$, 6000, and 4500 K, respectively) with a fixed UV flux for $T_{\text{eff}} = 6000$ K to show the “temperature effect.” (Color graphics available online at www.liebertonline.com/ast)
FIG. 6. Planetary temperature/altitude profiles for different stellar types showing the combined temperature and UV effect. (Color graphics available online at www.liebertonline.com/ast)

FIG. 7. Photochemical model results for the mixing ratios of the major molecules H₂O, O₃, CH₄, N₂O, CH₃Cl, and OH for each stellar spectral type in our grid of stars showing the combined temperature and UV effect. (Color graphics available online at www.liebertonline.com/ast)
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 $T_{\text{eff}} = 7000$, 6000, and 4500 K (representing high, mid, and low UV flux) with a fixed ATLAS photosphere model of $T_{\text{eff}} = 6000$ K. 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; for example, an F0V grid star emits $130 \times$ more flux in this wavelength range than a K7V grid star (Figs. 1 and 2).

The Chapman reactions are driven primarily by photolysis in this wavelength range, and the atmospheric 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 kilometers above the peak of the O3 concentration where both a high enough concentration of O3 and a high enough flux of photons is present. O3 abundance increases OH abundance, the primary sink of CH4 and CH3Cl. Figs. 5 and 7 show a corresponding decrease in those molecules for high-UV environment. O3 shields H2O in the troposphere from UV environments. Stratospheric H2O is photolysed by $\lambda<2000$ Å or reacts with excited oxygen, O(1D), to produce OH radicals. Accordingly, stratospheric H2O concentration decreases with decreasing UV flux. N2O decreases with increasing UV flux because of photolysis by $\lambda<2200$ Å. N2O is also an indirect sink for stratospheric O3 when it is converted to NO. Therefore, decreasing N2O increases O3 abundance. O2 and CO2 concentrations remain constant and well mixed for all stellar types.

3.2. The influence of stellar $T_{\text{eff}}$ on Earth-like atmosphere models (temperature effect)

To explore the effects of stellar $T_{\text{eff}}$ alone on the atmospheric abundance of different molecules, we combined specific photospheric ATLAS spectrum of $T_{\text{eff}} = 7000$, 6000, and 4500 K (representing high, mid, and low stellar $T_{\text{eff}}$) with a fixed UV data file of $T_{\text{eff}} = 6000$ K. The temperature/pressure and chemical profiles of this test are shown in panels (b) of Figs. 4 and 5. $T_{\text{eff}}$ affects H2O vapor concentrations due to increased evaporation for high planetary surface temperature, which is transported to the stratosphere. Figure 4 shows an overall increase in tropopause and stratopause height for low stellar $T_{\text{eff}}$ with corresponding hot planetary surface temperatures.

The response of O3 to stellar $T_{\text{eff}}$ is weak due to two opposing effects: high stellar $T_{\text{eff}}$ and corresponding low
planetary surface and atmospheric temperatures increase \( O_3 \) concentration by slowing Chapman reactions that destroy \( O_3 \), but also increase \( NO_x, HO_x, \) and \( ClO_x \) concentrations, which are the primary sinks of \( O_3 \) (see also Grenfell et al., 2007).

Both \( CH_4 \) and \( CH_3Cl \) show only a weak temperature dependence. The rate of the primary reactions of \( CH_4 \) and \( CH_3Cl \) with \( OH \) slows with decreasing temperature, causing an increase in \( CH_4 \) and \( CH_3Cl \) for lower planetary surface temperatures. \( N_2O \) displays a similar weak temperature effect.

All our simulations used a fixed mixing ratio of 355 ppm for \( CO_2 \) and 21% \( O_2 \). Since both \( O_2 \) and \( CO_2 \) 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

Figures 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 \( H_2O \) and \( CO_2 \) (see Table 2 and Fig. 6). The late K dwarf stars show in addition a near isothermal stratosphere.

Figure 7 shows the corresponding atmospheric mixing ratios versus height for the grid stars. The top height considered in our atmospheric models is 60 km for a Sun-like star, which corresponds to \( 10^{-4} \) bar (following Segura et al., 2003). For hotter stars, the stratosphere is warmer, which increases the pressure at 60 km to \( 4.0 \times 10^{-4} \) bar, while for cooler stars the pressure at 60 km decreases to \( 3.0 \times 10^{-5} \) bar.

Earth-like atmosphere models around hot grid stars show high \( O_3 \) concentration (see Table 2) and therefore strong temperature inversions due to the increased stellar UV flux (Fig. 6). Cooler stars often have stronger emission lines and higher activity. Accordingly, the two coldest grid stars in our sample (\( T_{eff}=4250 \) K and 4500 K) show a large \( O_3 \) abundance due to high stellar Ly \( x \) flux. In fact, the UV output of the coldest grid star, \( T_{eff}=4250 \) K, is almost \( 2 \times \) the
UV flux of the second coldest grid star, $T_{\text{eff}} = 4500$ K, also due to its younger age. Thus, there is more O$_3$ produced for the coldest star. However, in the 2000–3000 Å wavelength region these cold grid stars emit low UV flux and therefore produce near isothermal stratospheres (see also M dwarf models of Segura et al., 2005). The detailed effect of Ly α flux on the planet’s atmosphere will be modeled in a future study.

Earth-like atmosphere models around hot grid stars also show high OH concentrations due to a higher availability of high-energy photons, as well as O$_3$ and H$_2$O molecules (Fig. 7). Cold grid stars ($T_{\text{eff}} = 4250$ K) show higher OH concentration in the stratosphere than expected from an extrapolation from the other grid stars due to the increased O$_3$ and H$_2$O concentrations at those altitudes.

CH$_4$ abundance increases with decreasing stellar temperature, dominated by the effects of decreasing stellar UV. Stratospheric CH$_4$ decreases in atmospheric models around hot grid stars since both OH concentration and UV flux increase with stellar $T_{\text{eff}}$ and act as sinks of CH$_4$.

H$_2$O abundance in the troposphere is dominated by the surface temperature of the planet. Earth-like planet atmosphere models around cool grid stars generate warmer planetary surface temperatures and therefore high amounts of tropospheric H$_2$O. High UV flux generally decreases H$_2$O concentration in the stratosphere through photolysis, but increased O$_3$ concentrations provide shielding from the photolysis of H$_2$O. Also, cold grid stars ($T_{\text{eff}} = 4250$ K and 4500 K) show increased stratospheric H$_2$O concentration through increased vertical transport in the nearly isothermal stratospheres as well as production by stratospheric CH$_4$ [see, e.g., Segura et al. (2005) for similar behavior in planets around M dwarfs]. In particular, the atmospheric models for a planet around a $T_{\text{eff}} = 4250$ K grid star have a high OH concentration in the stratosphere due to increased O$_3$ and H$_2$O at those altitudes.

N$_2$O is primarily produced by denitrifying bacteria and has increased linearly due to agriculture since the preindustrial era at a rate of around 0.26% year$^{-1}$ (Forster et al., 2007). Up to about 20 km, there is no significant difference between stellar types in N$_2$O concentration. Figure 7 shows that above ~20 km a decrease in N$_2$O concentration occurs for atmospheric models of planets around hot grid stars but does not occur for those of cool grid stars, since UV is the primary sink of N$_2$O in the stratosphere. Below 20 km, N$_2$O is shielded from photolysis by the O$_3$ layer. Note that the general trend for increasing N$_2$O for colder grid stars reverses for our coldest grid star. This is due to the increased UV flux, which destroys N$_2$O, and an increase in O$_3$, which causes an increase in O(1D), another strong sink for N$_2$O.

CH$_3$Cl concentration decreases with increased stellar UV flux since OH acts as a sink for CH$_3$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 that has cloud layers analogous to Earth
[40% 1 km, 40% 6 km, and 20% 12 km 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 influence 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 and the ASTER Spectral Library (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., 2005; Pallé 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. Note that we use an Earth-sized planet to determine the specific flux and planet-to-star contrast ratio. A Super-Earth with up to twice Earth’s radius will provide up to 4× more flux and a better contrast ratio than shown in Figs. 8–12.

4.1. Earth-like VIS/near-IR spectra (0.4 to 2 μm)

Figure 8 shows spectra from 0.4 to 2 μm of Earth-like planets for both a clear-sky and Earth-analog cloud cover for the grid stars (F0V–K7V). The high-resolution spectra have been smoothed to a resolving power of 800 with a triangular smoothing kernel. Figures 8 and 9 show that clouds increase the reflectivity of an Earth-like planet in the VIS to near IR substantially and therefore overall increase the equivalent width of all observable features, even though they block access to some of the lower atmosphere.

Figure 9 shows individual features for the strongest atmospheric features from 0.4 to 4 μm for Earth-like planets orbiting the grid stars: O₃ at 0.6 μm (the Chappuis band), O₂ at 0.76 μm, H₂O at 0.95 μm, and CH₄ at 1.7 μm. The left panel of each row shows the relative flux as planet-to-star contrast ratio; the middle and right panel show the specific

\[^2\text{http://speclab.cr.usgs.gov/spectral-lib.html.}\]
\[^3\text{http://speclib.jpl.nasa.gov.}\]
top-of-atmosphere (TOA) 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 signal-to-noise ratio to be detected.

The 0.6 \mu m shallow O3 spectral feature depth increases with \textit{T}_{\text{eff}} of the host star 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 \mu m is constant, but the detectable 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 \mu m (shown) 0.8, 1.1, and 1.4 \mu m increases for planets orbiting cool grid stars due to their increased H2O abundance. The depth of the CH4 absorption feature at 1.7 \mu m increases with decreasing stellar \textit{T}_{\text{eff}} due to the increase of CH4 abundance.

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

4.2. Earth-like IR spectra, IR (4 to 20 \mu m)

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

Figure 11 shows individual features for the strongest atmospheric features from 4 to 20 \mu m for Earth-like planets orbiting the grid stars: O3 at 9.6 \mu m, CO2 at 15 \mu m, H2O at 6.3 \mu m, and CH4 at 7.7 \mu m for a cloud-free and Earth-analog 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, TOA flux for a clear and 60% cloud coverage case, respectively.

In the clear sky model, the depth of the O3 feature at 9.6 \mu m decreases for planetary models orbiting hot grid stars, despite increasing O3 abundance, due to lower contrast between the continuum and absorption layer temperature. For Earth-analog cloud cover, however, O3 is seen in emission for \textit{T}_{\text{eff}} \geq 6500 K due to the lower continuum temperature.

Due to the hot stratosphere for all grid stars with \textit{T}_{\text{eff}} > 6000 K, the CO2 absorption feature at 15 \mu m has a prominent central emission peak. Clouds reduce the continuum level and the depth of the observable CO2 feature.

The CH4 feature at 7.7 \mu m 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 5–8 \mu m. The depth of the H2O features at 5–8 and 18+ \mu m does not change.
significantly even though H$_2$O abundance increases for cool grid stars. Clouds reduce the continuum level and the depth of the observable H$_2$O features.

Figure 13 shows planet-to-star contrast ratio for Earth-analog cloud cover of an Earth-like planet from which the photometric precision required can be calculated. The planet-to-star contrast ratio is between $10^{-8}$ and $10^{-11}$ in the VIS/near IR 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.

4.3. The effect of clouds on Earth-like planet spectra from 0.4 to 20 $\mu$m

Figure 12 shows Earth-like planet spectra for 100% cloud cover at 1, 6, and 12 km from 0.4 to 20 $\mu$m for three sample grid stars with $T_{\text{eff}}=7000$ K (top), 5750 K (middle), and 4250 K (bottom). The clear sky spectrum is shown as a dashed line for comparison. Clouds increase the reflectivity of an Earth-like planet in the VIS to near IR 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 absorption features, even though they can increase the relative depth of a spectral feature due to lowering the continuum temperature of the planet.

Figure 14 shows the individual chemical absorption features as discussed in Sections 4.1 and 4.2 on a relative scale for H$_2$O, CO$_2$, O$_3$, CH$_4$, N$_2$O, and CH$_3$Cl from 0.4 to 20 $\mu$m to complement the spectra, shown in Figs. 5–9, that focus on the remote detectability of individual features for future space missions.

5. Discussion

When choosing IUE stars 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 chose 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 O$_2$ or O$_3$ and CH$_4$ for emergent spectra and secondary eclipse measurements requires observations in the IR or in the VIS/near IR up to 3 $\mu$m to include the 2.4 $\mu$m...
CH$_4$ feature in that spectral range. The strength of the absorption features depends on the stellar effective temperature of the host star and varies significantly between stellar types. In the IR, CH$_4$ at 7.7 $\mu$m is more detectable at low resolution for cool grid stars than hot grid stars. The 9.6 $\mu$m O$_3$ feature is deepest for mid to cool stars and becomes less detectable for hotter stars. However, around our hottest grid stars, the 9.6 $\mu$m O$_3$ feature becomes an apparent emission feature for cloudy atmospheres. The narrow O$_2$ feature in the VIS at 0.72 $\mu$m is of comparable strength for all grid stars. H$_2$O has strong features for all grid stars over the whole wavelength range.

N$_2$O and CH$_3$Cl have features from the near IR 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 to 0.75 $\mu$m 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 study, we did not model planets orbiting stars cooler than $\sim$4000 K to provide a consistent set of planetary models. As discussed by Segura et al. (2005), cool host stars with low UV flux provide an environment that leads to runaway CH$_4$ accumulation in the atmosphere; therefore the model for Earth-like planets around M dwarfs often uses abiotic CH$_4$ levels, which is not consistent with Earth-analog models used in this study. We will explore this effect in 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 and 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 $\times$ Earth’s radius and therefore up to 4 $\times$ the flux and planet-to-star contrast ratio levels quoted for Earth-sized planets shown in Figs. 8–14.

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 VIS 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 dayside and nightside. 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 \( T_{\text{eff}} = 7000, 5750, \) and 4250 K to show the effect of orbital position (see also Robinson et al., 2011). For quadrature, representing an average viewing geometry, the contrast ratios presented in Fig. 13 will be a factor of \( \approx 2 \) lower in the VIS. Assuming the planet has efficient heat transport from the dayside to nightside, 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 \( T_{\text{eff}} = 4250 \) K to \( T_{\text{eff}} = 7000 \) K in 250 K increments, comprehensively covering the full FGK stellar range. We discussed the detectable features for clear and cloudy atmosphere models and compared the effect of the stars’ SED and UV flux on both the atmospheric composition as well as the detectable atmospheric features in Sections 3 and 4. Increasing UV environments (generally coupled with increasing stellar \( T_{\text{eff}} \) for main sequence stars) result in increasing concentration of \( \text{O}_3 \) from photolysis; increasing stratospheric \( \text{H}_2\text{O} \) from \( \text{O}_3 \) shielding; increasing \( \text{OH} \) based on increased \( \text{O}_3 \) and \( \text{H}_2\text{O} \) concentrations; and decreasing \( \text{CH}_4, \text{CH}_3\text{Cl}, \) and \( \text{N}_2\text{O} \) from photolysis and reactions with \( \text{OH} \). Increasing stellar temperatures and corresponding decreasing planetary surface temperatures result in decreasing tropospheric \( \text{H}_2\text{O} \) due to decreased temperatures; decreasing stratospheric \( \text{H}_2\text{O} \) from transport; and decreasing reaction rates of \( \text{OH} \) with \( \text{CH}_4, \text{N}_2\text{O}, \) and \( \text{CH}_3\text{Cl} \). The overall effect, as the stellar effective temperature of the main sequence grid stars increases, is an increase in \( \text{O}_3 \) and \( \text{OH} \) concentration; a decrease in tropospheric \( \text{H}_2\text{O} \) (but an increase stratospheric \( \text{H}_2\text{O} \)); and a decrease in stratospheric \( \text{CH}_4, \text{N}_2\text{O}, \) and \( \text{CH}_3\text{Cl} \).

In the IR, the temperature contrast between the surface and the continuum layer strongly impacts the depth of spectral features. While \( \text{O}_3 \) increases for hotter main sequence stars, its detectable feature in the IR decreases due to the decrease temperature difference between the continuum and the emitting layer. For hot stars, with \( T_{\text{eff}} \geq 6750 \) K, the \( \text{O}_3 \) feature appears as emission due to the contrast to the continuum.

Our results provide 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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Author Disclosure Statement

No competing financial interests exist.

Abbreviations

IUE, International Ultraviolet Explorer; JWST, the James Webb Space Telescope; LW, longwave; SED, spectral energy distribution; SW, shortwave; TOA, top of atmosphere.

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