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Modelling the Diversity of Extrasolar Terrestrial Planets

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Abstract. As we prepare to undertake the observational search for extrasolar terrestrial planets, theoretical modeling studies can help to prepare us for the likely diversity of the extrasolar terrestrial planets. This diversity may arise as a function of planetary system architecture and formation history, which results in a variety of initial planetary properties, as well as stellar, planetary and biological evolutionary processes. Modeling of the physical and chemical processes of the planetary environment, and their interaction with the parent star, allows us to understand the nature of the planetary characteristics that indicate habitability and life, and how these manifest in the planetary spectra. Here we present disk-averaged spectra of planets in our own solar system, and models of the Earth through several eons to understand the types of planetary characteristics that are likely to be observed by planned planet detection and characterization missions.

Keywords. astrobiology, techniques: spectroscopic telescopes, instrumentation: spectrographs, Earth, planets and satellites: general, stars: planetary systems.

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1. Introduction

1.1. *The Search For Habitable Worlds*

The search for habitable or Earth-like planets beyond our Solar System will be conducted with space-based observatories and advanced observing techniques. Yet, the planetary characteristics sought, the analysis tools used, and the ultimate interpretation of what we find must rely on an interdisciplinary synthesis of theory and existing observation.

The NASA Terrestrial Planet Finder Coronagraph (TPF-C), and ESAs Darwin and NASAs Terrestrial Planet Finder Interferometer (TPF-I) missions will have the capability to directly detect and characterize terrestrial planets around several hundred nearby stars, and both will have low-resolution spectral capability (($R \sim 70$ in the visible, and $R \sim 20$ in the mid-infrared (MIR)). TPF-C's visible wavelength observations will be sensitive to surface and atmospheric composition, while TPF-I and Darwin's MIR capability is most sensitive to surface and atmospheric temperatures and atmospheric trace gases.

Extrasolar terrestrial planets will appear as unresolved point sources, precluding spatial resolution of continents, oceans or clouds. The planet's characteristics, including life, must be inferred from a spectrum averaged over the visible disk. Self-consistent models of extrasolar terrestrial planet environments must therefore by combined with advanced remote-sensing retrieval methods to identify signs of habitability and life in the context of the planetary characteristics that affect this disk-averaged spectrum, especially as the spectra will also likely significantly time-averaged as well. We also cannot expect that the planets found will be similar to known Solar System bodies, due to likely differences in planetary architecture, initial composition, evolutionary development, and age.

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Our search strategy, detection, and analysis techniques for extrasolar terrestrial planets must be flexible enough to determine the characteristics of worlds completely unlike our own. Self-consistent models of planet formation, climate, and atmospheric compositions can inform these search strategies by using a specific planetary context (stellar type, mass, orbital geometry, bulk composition) to help define the plausible range of planetary environmental conditions and their resulting disk-averaged spectral signatures.

1.2. *The Potential Diversity of Other Worlds*

The Earth is the only known habitable, living world, and yet the complexity of terrestrial planet structure, composition and processes, with myriad possibilities for origins and evolution, suggest that an Earth twin is unlikely to be the only other habitable planet found. Recent ground-based observations show an unexpected diversity of extrasolar planetary system architectures (Marcy *et al.* 2005), that modeling indicates translate into differences in the formation, composition, evolution and characteristics of terrestrial planets. In particular, initial planetary mass, the initial volatile inventory, and the subsequent evolution of volatile delivery may differ significantly, and can be affected by stochastic variations during formation (Wetherill, 1996; Morbidelli *et al.*, 2000), or systematic variations due to the initial disk mass and metallicity, and the location and orbits of Jovian planets (Chambers and Cassen, 2002; Levison and Agnor, 2003; Raymond *et al.*, 2004).

While terrestrial planets more massive than the Earth are not represented in our Solar System, they are seen in planet formation simulations (c.f. Raymond *et al.*, 2004). The recent discovery of a 7.5 Earth mass planet provides the first evidence of a likely large-mass terrestrial planet (Rivera *et al.*, 2005). The environmental characteristics of these larger planets are unknown, but are important to model, as they are likely to be the first terrestrial planets detected via astrometry and characterized via direct detection.

Initial volatile inventory is also strongly affected by the planetary system architecture. For planetary systems with a hot Jupiter, or an eccentric outer Jovian, the formation of water-rich worlds in the habitable zone can become increasingly more difficult (Raymond *et al.*, 2004; Raymond *et al.*, 2005a) favoring the formation of water-poor worlds. Yet, for Solar Systems similar to our own, recent simulations suggest that the majority of terrestrial planets are formed with a higher water inventory than our current Earth (Raymond *et al.* 2006). Retention of volatiles over the course of evolution of the planet may then be a significant factor in continued habitability and planetary diversity.

Evolutionary processes therefore provide an additional mechanism for planetary diversity, as the divergent evolution of Venus and Earth, near "twins" in size, mass and bulk composition, shows. The planetary state is dictated by both the planets characteristics and its evolving interaction with its parent star, including possible planetary migration, atmospheric mass loss, large impacts and other exogenic processes. The interaction of life with our evolving planet has resulted in a diversity of planetary states at different points in our history. The more stable and long-lived the planetary environmental state, the more likely it is to be seen in astronomical observations. As our neighboring stars have ages from newborn to 10Gy old (Nordstrom *et al.*, 2004) the planned planet detection and characterization missions will have the exciting opportunity to observe planets at different stages of planetary and biological evolution.

2. Characterizing Terrestrial Planets

2.1. *Planetary System Environments*

For the planned planet detection and characterization missions, the target stars to be searched for planets will likely be well characterized prior to mission launch. With regard to planetary habitability, the star's most important characteristics are its full-wavelength spectrum and its activity level (e.g. flares, luminosity variations). Other aspects of the planetary system environment that will affect habitability include the presence of small bodies and the presence, nature and orbits of any giant planets in the system.

2.2. *The Signs of Habitability*

For extrasolar terrestrial planets, habitability is defined as the environmental conditions required to maintain liquid water on the surface of the planet. Photometric variability may provide clues to planetary surface inhomogeneity from continents and oceans (Ford *et al.*, 2001), although to first order, cloud-cover will produce the majority of this variability (Tinetti *et al.*, 2006) and repeated observations at relatively high temporal resolution will be needed to discriminate surface from cloud effects.

Once a terrestrial planet is identified, we will use both models and observations to attempt to determine if its surface temperature and pressure are consistent with liquid water. From Earth and planetary studies, we know that surface temperature (and possibly pressure) are the product of the planetary global energy balance, which depends on the planets orbit(which gives planetary distance, and therefore solar insolation, as a function of time), the properties of the parent star, the atmospheric mass and composition, and the planetary surface properties (albedo, thermal inertia). Direct observation of surface temperature at optical and infrared wavelengths can be thwarted by the presence of clouds, or a thick, absorbing atmosphere. Direct measurements of atmospheric pressure are also difficult, especially in the presence of clouds. For terrestrial planets, clues to atmospheric pressure may be provided from the slope of Rayleigh scattering in the 0.4-0.7μm region (Arnold *et al.*, 2002, Woolfe *et al.*, 2002). However, this spectral region is also sensitive to surface absorption from iron oxides (as seen on Mars) and absorption by ozone and other trace gases (SO_2, NO_2) in both a clear and cloudy atmosphere.

Spectra of Earth provide clues to habitability. In the MIR, strong CO_2 absorption at 15μm indicates the presence of an atmosphere and provides clues about its thermal structure. For Earth, the structure of this broad absorption feature indicates a warm emitting surface that is overlain by a cooler troposphere, and a hotter stratosphere. A hotter stratosphere may be due to the presence of a UV absorber, like the Earth's O_3, which can act as a UV shield for the surface below. Water vapor is also a spectral indicator of potential habitability, and can be seen at both MIR and visible wavelengths (Figure 1). There may, however, be other indicators of habitability, or conversely, other atmospheric and surface constituents that, if present, would indicate that liquid water was unlikely to exist on the planetary surface. For Venus, although both CO_2 and small amounts of H_2O can be seen in the spectrum, the simultaneous presence of SO_2 and H_2SO_4, both unstable in the presence of liquid water, indicates that surface water is unlikely.

2.3. *Biosignatures: The Signs of Life*

The concept of an astronomical biosignature was introduced as early as 1965 when Lovelock (1965) proposed that the life on a planet would change the atmospheric composition by many orders of magnitude. Such changes could be recognized even at astronomical distances. Initial identification and estimates of biosignature detectability for TPF and Darwin are described in Des Marais *et al.*, 2002 and Selsis *et al.*, 2003. Here we define three different types of biosignatures; atmospheric, surface, and temporal.

Atmospheric Biosignatures: are constituents in the planetary atmosphere that are significantly out of chemical equilibrium, or likely byproducts of life processes. The abundant O_2 in our atmosphere is considered a good biosignature (Lovelock & Margulis, 1974; Des Marais *et al.*, 2002), but both CH_4 and N_2O, especially when seen in the presence

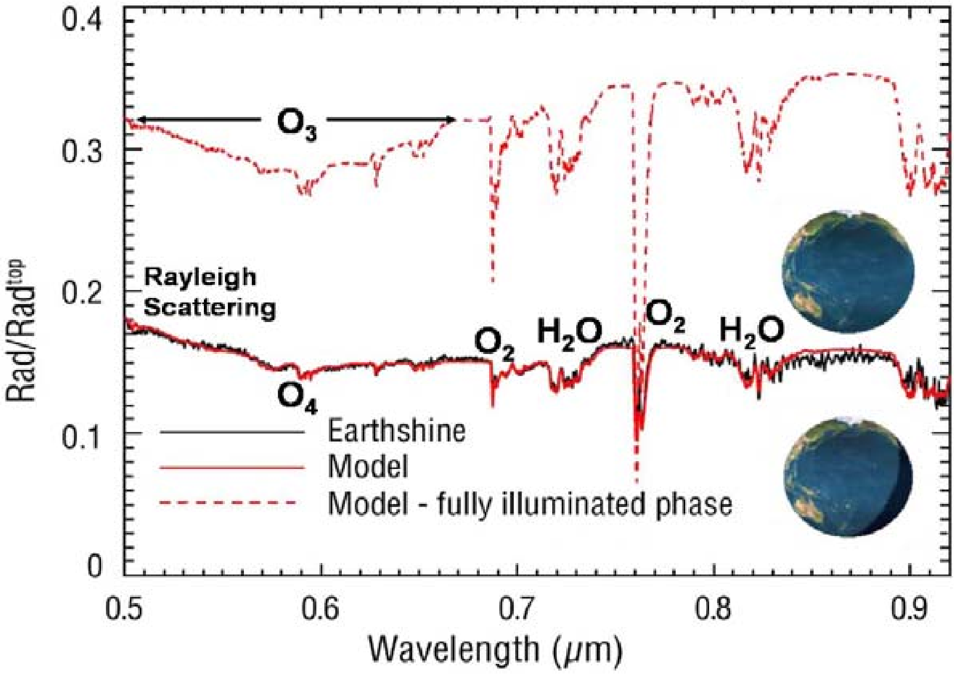

Figure 1. The observed disk-averaged Earthshine spectrum (from Woolf *et al.*, 2002), fit with synthetic spectra generated by the VPL 3-D Earth model for the observed gibbous phase, and the same model extrapolated to full-phase (after Fig 8(c), Tinetti *et al.*, 2006). Water vapor can be clearly seen, especially at the longer wavelengths, and the biosignatures O_2, O_3 and O_4 are also indicated. The pressure sensitive O_2 dimer (O_4) may become more detectable in higher mass atmospheres.

of O_2, provide a much stronger potential biosignature because they indicate a chemical disequilibrium (Lovelock & Margulis, 1974).

Surface Biosignatures: are spectral features in the surface reflectance that are associated with bio-pigments (e.g. chlorophyll), or are due to the physical structure of life, such as the *red edge* reflectivity of leaves (Gates *et al.* 1965; Seager *et al.*, 2005). Although the red edge is seen near 0.7μm on Earth, it could be shifted for extrasolar planets, due to different planetary atmospheres and host star spectra(Wolstencroft & Raven, 2002)

Temporal Biosignatures: are atmospheric or surface characteristics that change as a function of time due to seasonal variations in biomass or planet-wide life processes. On the Earth, seasonal periodicities in both atmospheric CO_2 and CH_4 are associated with respiration in the land biosphere.

False Positives: occur when abiotic planetary processes mimic a biosignature. Examples include the abiotic production of CH_4, O_2 production during loss of an ocean, surface mineral reflectivities, and seasonal changes in planetary reflectivity or composition induced by dust storms or photochemistry. Once modeling has identified the nature and likelihood of false positives, observations can be planned to ensure sufficient wavelength coverage and sensitivity to help to rule them out.

3. Modelling: The Virtual Exploration of New Worlds

While the planned NASA and ESA mission suite will obtain the first data on the range of extrasolar terrestrial planet environments, these technically-challenging missions have decades-long lead times. The current field of extrasolar terrestrial planet characterization consequently relies on modeling investigations which allow us to explore a larger range of planetary environments and spectra, including planets of different masses and ages. Models can also be used to visualize even the more familiar Solar System planets as disk-averages, over larger wavelength ranges and from different viewing geometries than are currently readily available.

Modeling planetary spectra for extrasolar terrestrial planets involves three major steps, input data collection, generation of a planetary environment (surface and atmospheric temperature structure and composition), and spectral generation. The input data includes stellar spectra and the optical and spectral properties of the constituent gases and aerosols. As planetary habitability is affected by both the UV portion of the spectrum (photochemistry, surface incident radiation), and the longer wavelengths (global energy balance and climate), the full wavelength range for the input stellar spectra is required, via both data gathering and modeling. For the planet models shown here, we have used stellar spectra generated by M. Cohen (http://vpl.ipac.caltech.edu/spectra/stellar) and molecular linelists from the HITRAN database (Rothman *et al.*, 2005)

To generate the planetary environment, coupled-climate-chemistry models are used. These models produce vertical profiles for atmospheric temperature, pressure and constituents. Fluxes of gases at the atmospheric boundaries (surface and exosphere) can be specified, or generated by models that are coupled to the climate-chemistry model. Coupled climate-chemistry models are more likely to produce temperature and constituent profiles that are self-consistent with each other and the incoming stellar radiation. This is particularly important for determining the detectability of planetary spectral features in the MIR, where the atmospheric temperature structure can enhance or reduce the strength of constituent absorption bands. Here we have principally used a 1-D (vertical) coupled climate-chemical Radiative-Convective Equilibrium model developed by J. Kasting, and additional models as specified below.

The planetary temperature, pressure and constituent profiles, and stellar spectra are input to radiative transfer models which generate synthetic spectra of the planet. Here we have used a radiative transfer code based on the Spectral Mapping Radiative Transfer or SMART code developed by D. Crisp (Meadows & Crisp, 1996; Crisp, 1997).

4. Synthetic Spectra of Terrestrial Planets

To understand the spectra that might be seen by extrasolar terrestrial planet characterization missions, observations, data and models can be combined to progressively move from studying objects we know relatively well, such as the Earth and Solar System planets, to planetary environments that are less well known, such as the Earth's environment during its 4.6Gy history, and planets around stars of different spectral type.

4.1. *Synthetic Spectra of Solar System Planets*

Figure 2 shows full resolution synthetic spectra for terrestrial planets in our Solar System from 0.5 to 1.7μm. The Mars and Earth spectra are fully 3-dimensional radiative transfer simulations of the disk-averaged spectrum using atmospheric GCM or observational data as input. The spectra have been validated to spacecraft and Earthshine observations (Tinetti *et al.*, 2005, 2006). The Venus spectrum is a simulated disk-average for an average solar illumination and viewing angle. Also included is a 3-D model disk-average of the Earth as it would appear if completely covered by high cirrus clouds.

This figure shows the remarkable diversity of terrestrial planet spectra, even in our own Solar System. The Venus spectrum is dominated principally by strong CO_2

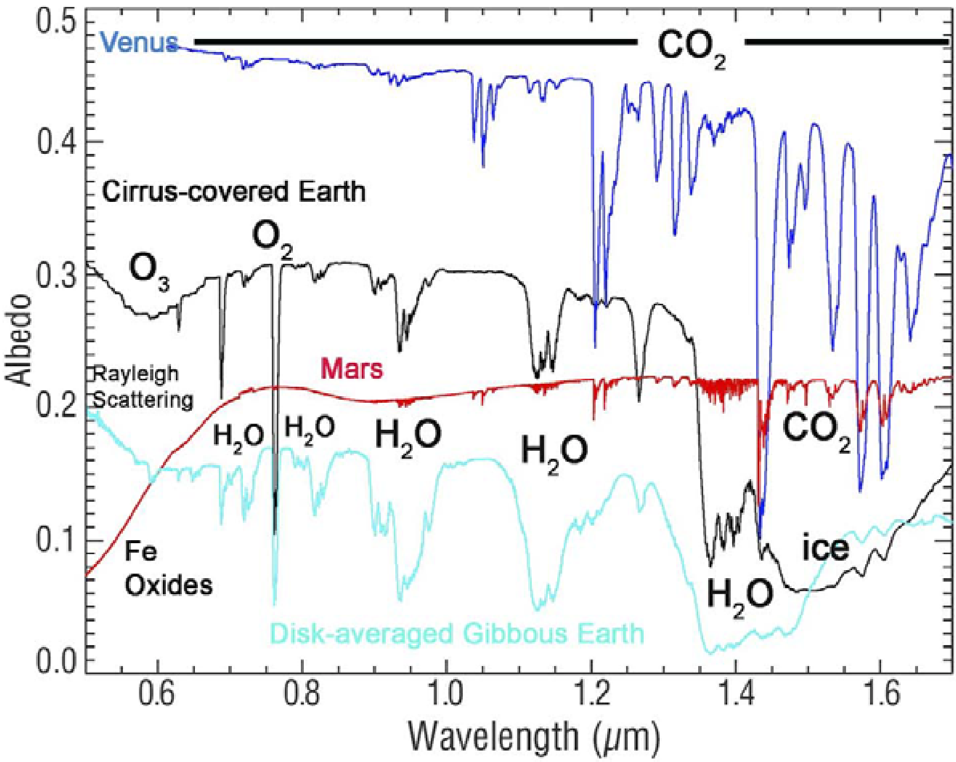

Figure 2. Synthetic albedo spectra of Solar System terrestrial planets generated by the Virtual Planetary Laboratory (VPL). The Mars and Earth spectra are from fully-spatially resolved models that have been degraded to the disk average (Tinetti *et al.*, 2005, 2006). Also shown is a model of a cirrus cloud covered Earth, which exhibits enhancements in the O_3 absorption from 0.5-0.7μm and water ice bands near 1.55μm.

absorption, although extremely weak water bands can also be seen. As Venus represents the likely end state for terrestrial planet evolution, this type of environment and spectrum may be relatively common for extrasolar terrestrial planets. The Mars spectrum is also dominated by CO_2, but these relatively weak features are only likely to be detected longward of 1.4μm. The Earth spectra are dominated by water vapor, and Earth's O_2 biosignatures are clearly seen. In Earth's spectrum from 0.5-0.7μm, ozone absorption and Rayleigh scattering are both present. However, in the presence of high clouds, the observable atmospheric column is reduced, and the Earth's Rayleigh scattering slope is correspondingly diminished. However, due to multiple scattering within the clouds, the O_3 absorption is enhanced. Attempting to use Rayleigh scattering as an indicator of atmospheric density is also difficult for Venus-like and Mars-like planets. In the case of Venus, the planetwide cloud-deck truncates the atmospheric column, and the unknown UV absorber reduces the albedo of the planet shortward of 0.55μm. For Mars, strong iron oxide absorption from the surface dramatically reduces the albedo of the planet shortward of 0.7μm.

Figure 3 shows a comparison of Earth and Venus with the smaller, CH_4-dominated bodies, Titan and Neptune. The planetary spectra were convolved with a triangular slit function to achieve a constant wavenumber resolution corresponding to R$\sim$70 at 0.76μm. The Venus and Earth models are as for Figure 2 above, and the Neptune and Titan input albedos were taken from observations (Karkoschka, 1994).

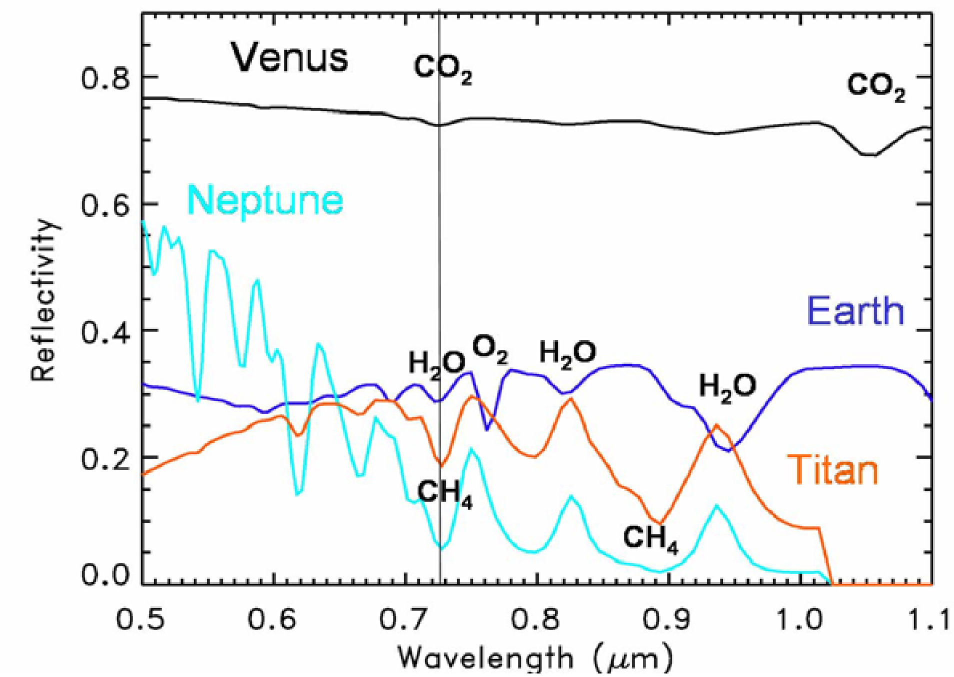

Figure 3. Synthetic spectra at R∼70 of the Earth (Tinetti et al., 2006) and Venus compared with measured albedos for Neptune and Titan (Karkoshka,1994).

Titan also shows a downturn due to absorption in the Rayleigh scattering region. Note also that at this resolution, absorption at 0.725μm is variously due to CO_2 (Venus), H_2O (Earth), or CH_4 (Titan and Neptune), depending on the different planetary composition. This redundancy however can be quickly overcome by searching for corroborating bands of each candidate molecule elsewhere in the spectrum, and argues for making characterization measurements over as large a wavelength range as possible.

4.2. *The Earth Through Time*

The Earth's history provides a suite of environments different to the modern Earth, which serve as analogs for habitable extrasolar planets. Prior to 2.3 billion years ago (Gya) the Earth's atmosphere likely had little O_2, and higher concentrations of CH_4 and CO_2. During the Proterozoic period, O_2 levels rose, but CH_4 levels may have remained high. To simulate spectra for the Earth's history, we used our radiative transfer model to generate synthetic spectra from a climate-chemistry model of the early Proterozoic environment (Pavlov et al., 2003; Segura et al., 2004) and a coupled atmosphere-ecosystem model for the Archean (Karecha *et al.*, 2005). For the Proterozoic, atmospheric O_2 was at 10% of present levels, with 100ppm of CH_4. For the Archean, the atmosphere was assumed to be 99.8% N_2, with 2000ppm of CO_2, 1000ppm of CH_4 and 100ppm of H_2. The resulting spectra for cloud-free cases over an ocean surface are shown in Figure 4 (vis-NIR) and in Figure 5 (MIR) (see also Kaltenegger *et al.*, this proceedings).

In the visible/NIR, one of the largest differences between the spectra of the three eons can be seen in the 0.5-0.7μm range, where the decreasing column depth of ozone from the modern to the Archean eon causes the slope of the spectrum to change significantly. In the modern and Proterozoic eons, O_2 can be seen at 0.76μm, although significantly diminished in the Proterozoic, but is not present in the Archean. Similar behaviour is

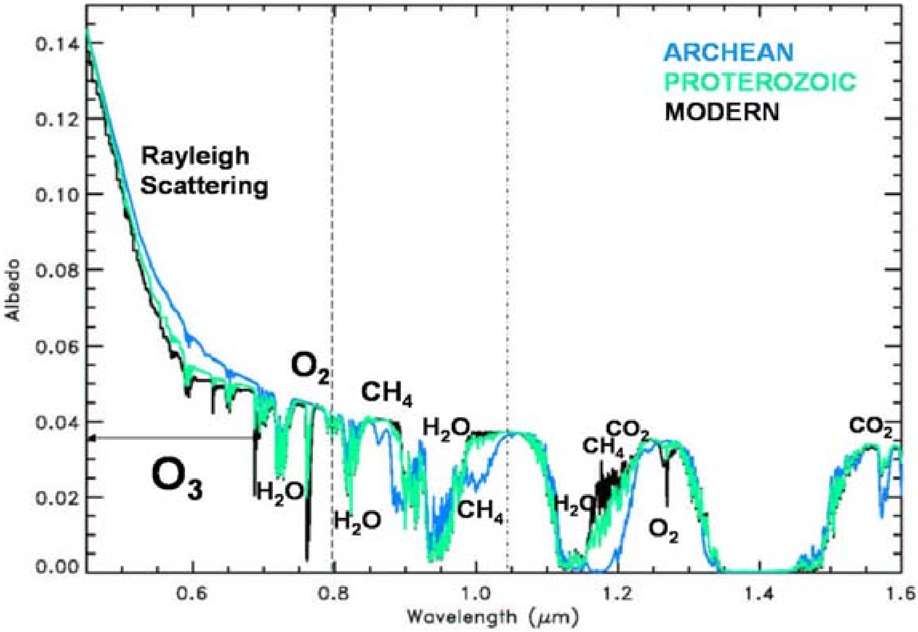

Figure 4. Synthetic visible wavelength spectra of the cloudless Earth during the late Archean (3.2-2.3Gya), Proterozoic (2.3-0.8 Gya) and Modern (present day) eons.

seen for the 1.27μm O_2 band. CH_4 absorption changes markedly throughout the Earth's history, with the strongest absorption seen in the Archean. For a TPF-C wavelength range, changes in atmospheric CH_4 abundance are most readily seen near 1.18μm, although strong bands also occur near 1.0μm and 0.88μm. Changes in CO_2 abundance are also seen in the spectra, although relatively weak. The strongest band is at 1.57μm with a weaker effect seen near 1.24μm. Note also that although CO_2 is visible at 1.05μm in the Venus spectrum (Figure 2) that band is typically extremely weak at Earth CO_2 concentrations and likely to be undetectable in Earth twins.

The MIR spectra are dominated by the bands of CO_2, CH_4, O_3 and H_2O. As we move back in time, the CO_2 band strengthens as the atmospheric CO_2 concentration increases. Similar behavior is also seen in the CH_4 absorption near 7.7μm. Interestingly, the O_3 absorption does not decrease in strength in the Proterozoic, even though the oxygen abundance of the atmosphere has been decreased ten-fold. This is due to both the non-linear relationship between oxygen concentration and ozone production, and the coupled effects of reduced ozone and reduced stratospheric temperature, which enhances absorption of the hotter surface radiation. Consequently, detection of the classic atmospheric biosignature, the simultaneous presence of CH_4 and O_2, or its proxy O_3, may be easier in a Proterozoic type environment than for modern-day Earth.

4.3. *Earth-like Planets Around Other Stars*

Planetary modeling also allows us to explore the interaction between terrestrial planets and the spectral energy distributions of their host stars. Segura *et al.* (2003, 2005) used coupled-climate chemistry models to explore the equilibrium atmospheric states of an Earth-like planet around F, G, K and active M stars. The planets modeled had an atmospheric composition and similar surface fluxes of biogenic gases to modern-day Earth. However, the modeled interaction of the planet with the spectral energy distribution of

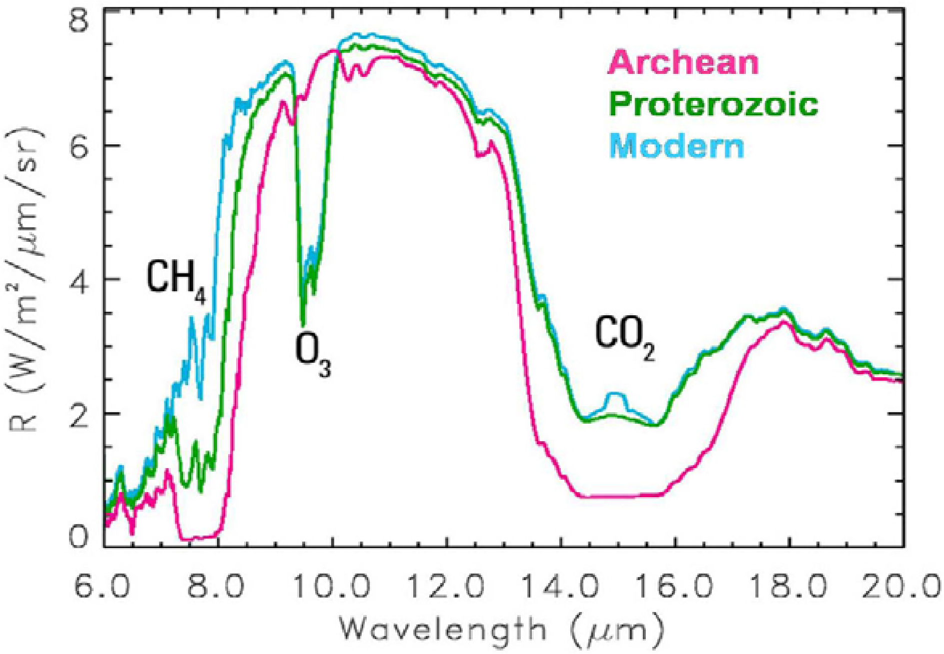

Figure 5. Synthetic mid-infrared wavelength spectra of the cloudless Earth during the late Archean (3.2-2.3Gya) Proterozoic (2.3-0.8 Gya) and Modern (present day) eons.

the parent star resulted in photochemistry that preferentially enhanced the atmospheric lifetimes of some biogenic gases (CH_4, and CH_3Cl) over others (N_2O) around K and M stars. This was shown to increase the detectability of atmospheric biosignatures that are only present trace quantities in the Earths present atmosphere for planets around K and M stars (see, for example, Figures 5-8 from Segura *et al.*, 2005)

5. Conclusions

Although our Solar System provides an excellent starting point from which to understand terrestrial planet spectra, extrasolar terrestrial planets may have different masses, orbits, ages and compositions, and be found in planetary systems unlike our own. Until the TPF and Darwin missions launch, modeling will allow us to explore a wider diversity of planets, and provide a basis to interpret and constrain the first order characterization data obtained by these missions. Modeling of the Earth's history and planets around other stars has already shown us that for Proterozoic-like periods and for planets around late type stars, life may be easier to detect than for the present day Earth. Finally, the diversity of planetary systems found so far indicates that we need to understand the effects of metallicity on planet formation, the processes and outcomes of planetary migration, and be flexible enough to characterize planets in planetary systems with architectures, orbits and evolutionary histories that may be quite unlike those currently known.

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Discussion

HEAP: Have you modeled planets around stars of different metallicity?

MEADOWS: Not yet. Although some of the planetary spectra I showed are modeled around stars of different spectral type, the planets themselves are Earth-like, and a direct connection between planetary composition and the formation history of the planet has not been made. However, VPL team members Raymond and Kress are collaborating to couple planet formation and disk chemistry models to generate planetary bulk-compositions consistent with the stellar metallicity. These planets will then serve as the starting point for our climate-chemistry, planetary evolution and spectral models.