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Sensitivity of biosignatures on Earth-like planets orbiting in the habitable zone of cool M-dwarf Stars to varying stellar UV radiation and surface biomass emissions

J.L. Grenfell [a,*,1], S. Gebauer [a], P. v. Paris [b], M. Godolt [a,1], H. Rauer [a,b]

[a] Zentrum für Astronomie und Astrophysik, Technische Universität Berlin (TUB), Hardenbergstr. 36, 10623 Berlin, Germany
[b] Institut für Planetenforschung, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Rutherford Str. 2, 12489 Berlin, Germany

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ABSTRACT

We find that variations in the UV emissions of cool M-dwarf stars have a potentially large impact upon atmospheric biosignatures in simulations of Earth-like exoplanets i.e. planets with Earth's development, and biomass and a molecular nitrogen–oxygen dominated atmosphere. Starting with an assumed black-body stellar emission for an M7 class dwarf star, the stellar UV irradiation was increased stepwise and the resulting climate-photochemical response of the planetary atmosphere was calculated. Results suggest a "Goldilocks" effect with respect to the spectral detection of ozone. At weak UV levels, the ozone column was weak (due to weaker production from the Chapman mechanism) hence its spectral detection was challenging. At strong UV levels, ozone formation is stronger but its associated stratospheric heating leads to a weakening in temperature gradients between the stratosphere and troposphere, which results in weakened spectral bands. Also, increased UV levels can lead to enhanced abundances of hydrogen oxides which oppose the ozone formation effect. At intermediate UV (i.e. with ×10 the stellar UV radiative flux of black body Planck curves corresponding to spectral class M7) the conditions are "just right" for spectral detection. Results suggest that the planetary ozone profile is sensitive to the UV output of the star from ~200–350 nm.We also investigated the effect of increasing the top-of-atmosphere incoming Lyman-α radiation but this had only a minimal effect on the biosignatures since it was efficiently absorbed in the uppermost planetary atmospheric layer, mainly by abundant methane. Earlier studies have suggested that the planetary methane is an important stratospheric heater which critically affects the vertical temperature gradient, hence the strength of spectral emission bands. We therefore varied methane and nitrous oxide biomass emissions, finding e.g. that a lowering in methane emissions by ×100 compared with the Earth can influence temperature hence have a significant effect on biosignature spectral bands such as those of nitrous oxide. Our work emphasises the need for future missions to characterise the UV of cool M-dwarf stars in order to understand potential biosignature signals.

1. Introduction

Finding evidence of life on an exoplanet is a fundamental goal of exoplanet science. Planets orbiting in the Habitable Zone (HZ) of cool M-dwarfs are potentially favoured targets (Scalo et al., 2007) due to their low planet to star flux contrast ratios, but there are many proposed properties of these systems which could impact their habitability e.g. regarding their possible tidal-locking (e.g. Kasting et al., 1993; Selsis et al., 2007), the potentially high influx of flares (e.g. Segura et al., 2010) and/or cosmic rays into the planetary atmosphere (e.g. Grenfell et al., 2012), or their ability to retain atmospheres (Lammer et al., 2007) to name but a few. Atmospheric biosignatures are species e.g. ozone (O_3) or nitrous oxide (N_2O) which, if present in suitable amounts in a planetary atmosphere may suggest the presence of life. A possible modelling approach (e.g. Segura et al., 2003) given the complications involved is to assume the Earth's development and biomass and then to allow the atmosphere to adapt e.g. to the incoming stellar spectrum. Earlier model studies (Segura et al., 2005; Segura et al., 2010; Rauer et al., 2011) applied this approach to focus on biosignature responses and spectra for Earth-like planets orbiting in the Habitable Zone (HZ) of M-dwarf stars.

Planetary atmospheric biosignature species may respond very sensitively to Ultra-Violet (UV) emissions from the central star since in these wavelengths they are either photodissociated directly or there occur photochemical reactions which affect their

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[*] Corresponding author. Tel.: +49 30 314 25463; fax: +49 30 314 24885.
E-mail address: lee.grenfell@dlr.de (J.L. Grenfell).

[1] Now at Institut für Planetenforschung, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Rutherford Str. 2, 12489 Berlin, Germany.

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abundance. The cooler M-dwarf stars are statistically older and burn more slowly compared with lower spectral classes. They have more developed convection zones and possibly larger differences in UV between flaring and quiet states. Whereas M-dwarf stars with spectral classes M6 and M7 likely possess very active chromospheres (Reid and Hawley, 2005) which implies strong UV emissions, the M8 and M9 spectral classes have less active chromospheres (e.g. Kruse et al., 2010). There are only limited observations of stellar UV emissions available (mostly for active M-dwarf stars with low to mid-range spectral classes) from which one can compile spectra and calculate the planetary atmosphere e.g. for AD-Leonis (ADL) (Segura et al., 2005), for GJ-581 (von Paris et al., 2010), and recently, for nearby M-dwarf stars (France et al., 2012). Some model studies (e.g. Rauer et al., 2011; Belu et al., 2011; Kaltenegger and Traub, 2009) therefore assumed a black-body spectrum as a first approach. However, they acknowledged that some deviations from such a spectrum may occur, not only for M-dwarf chromospheres which contribute to the UV emission, but also in their photospheres in the visible and IR due to the presence of stellar absorption lines. For the cooler M-dwarf stars (spectral classes M6-M7 and above), no UV observations currently exist.

In this work we concentrate on the M7 stellar class because this was a particular focus in recent modelling studies (e.g. in Rauer et al., 2011; Grenfell et al., 2013) and are particularly favourable targets. France et al. (2013) observed stellar flux for spectral classes ~M3 to M5, suggesting rather flat spectra with no significant strong jumps in UV. For M7, although observations in the near UV (defined as in France et al., 2013) are lacking, there are theoretical grounds (see e.g. Kaler, 2001) which suggest a (possibly) strong rise in stellar near UV ($\lambda < \sim 350$ nm) for ascending red-dwarf stellar classes M5→M6→M7. Dynamo theory of stellar magnetism suggests that the increased stellar rotation together with the deeper convection leads to a strengthening in the M7 chromospheres (possibly due to changes in magnetic re-connection) relative to the underlying photospheres. Although the dynamo theory has its limitations, on the above points there is general accord. Chromospheres can be very hot i.e. temperatures of several tens of thousands of degrees and emit strongly in the UV. We investigate the uncertainty in the stellar input radiation on the atmospheric biosignatures of the planet in two ways. First, we investigate uncertainty in the *slope* in input UV from 350 to 300 nm. Second, we investigate the effect of increasing stellar radiation ($\lambda < 300$ nm) by a factor of ×10, ×100 and ×1000. Lyman-α emissions from the central star may also impact planetary biosignatures although identifying the Ly-α emission from M-dwarf stars is very challenging e.g. due to uncertain absorption through the Interstellar Medium (e.g. Linsky, 2011). Finally, in addition to the effect of incoming UV on biosignatures, previous model studies (Grenfell et al., 2011; Grenfell et al., 2013; Rauer et al., 2011) also noted the potential importance of climate-chemical feedbacks which depend e.g. on surface biomass emissions and stellar insolation.

In this work we build on Rauer et al. (2011) who modelled atmospheric spectra and investigated spectral signals of biosignatures and related species assuming black-body Planck curves for a range of M-dwarf spectral classes up to M7. We start with a planetary atmosphere having Earth's biomass and an incoming top-of-atmosphere (TOA) stellar irradiation corresponding to a blackbody of a cool M-dwarf star with spectral class M7, we then vary three parameters, namely (1) the UV TOA incoming stellar radiation (see Fig. 1 and text above), (2) the TOA stellar Lyman-α flux alone and (3) the planetary surface biomass emissions, namely for methane (CH_4) and N_2O. CH_4 was found by Rauer et al. (2011) to strongly affect stratospheric temperatures hence the O_3 spectral band; N_2O is varied to investigate whether it is a “good biosignature” (i.e. for which the atmospheric abundance should respond sensitively to the biomass input). We discuss these effects upon both atmospheric biosignature abundances and theoretical spectra. Section 2 gives the model description and scenarios, Section 3 presents results and Section 4 gives a discussion and conclusions.

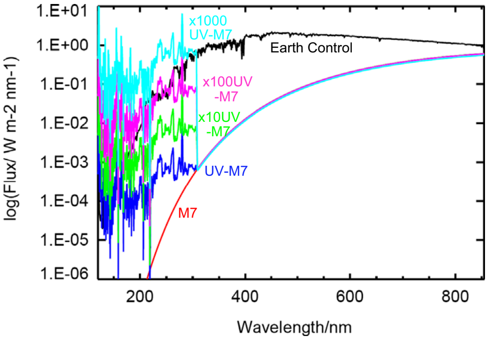

Fig. 1. Logarithm (log10) of Planetary Top-of Atmosphere (TOA) incoming high resolution stellar spectral flux (Wm^{-2} nm^{-1}).

2. Model descriptions, methods and about the runs

2.1. Atmospheric model description

The basic model version is described in Rauer et al. (2011) and is based on earlier versions described in Segura et al. (2003) and Kasting et al. (1993).

The Climate Module is a global-mean stationary, hydrostatic column model of the atmosphere from the surface up to 6.6×10^{-5} bar (for the Earth this corresponds to a height of about 70 km) with starting composition, pressure, and temperature based on the US-standard atmosphere (1976). Radiative transfer is based on the RRTM (Rapid Radiative Transfer Module) for the thermal radiation (see Mlawer et al., 1997) which extends from 3.07 to 1000 μm. The shortwave radiation scheme consists of 38 spectral intervals for the major absorbers extending from (237.6 nm–4.545 μm) and includes Rayleigh scattering for N_2, O_2, and CO_2 with cross-sections based on Vardavas and Carver (1984) and assumes a solar-zenith angle of 60°. For the Earth control scenario, a solar spectrum based on Gueymard (2004) is employed. See Section 2.3 for details of the M-dwarf spectra used. In the troposphere, convective adjustment to the moist adiabatic lapse rate is carried out and the water vapour concentrations are calculated from a relative humidity profile based on Earth observations (Manabe and Wetherald, 1967). Clouds are not included explicitly, although these are considered in a straightforward way by adjusting the surface albedo to attain the mean surface temperature of Earth (288 K) for the Earth around the Sun run (Earth control). After converging, the climate module outputs temperature, pressure, and water abundances as input for the chemistry module.

The Chemistry Module was described by Pavlov and Kasting (2002). The scheme includes 54 chemical species and more than 200 chemical reactions with kinetic data taken from the Jet Propulsion Laboratory (JPL) (2003) Report. The chemistry module assumes a planet with an Earth-like development, that is, with an N_2–O_2 dominated atmosphere, etc. The reaction scheme reproduces modern Earth's atmospheric composition with a focus on biomarkers (e.g., O_3, N_2O) and key greenhouse gases such as CH_4. The chemical module calculates the steady-state solution of the usual 1D continuity equations by an implicit Euler method. Mixing between adjacent layers is parameterized via Eddy diffusion coefficients. From a total of 54 chemical species, 34 are “long-lived,” that is, their concentrations are obtained by solving the full continuity equation. Finally, three species are set to constant abundances

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