3D Modelling of the Impact of Stellar Flares on Earth-like Rocky Planets Orbiting M Dwarf Stars

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Introduction

M dwarf stars are an important target for current exoplanet research. Due to their high abundance and low brightness, many exoplanets are known to orbit such stars.
A large fraction of M dwarfs are known to exhibit stellar flares (*Günther et al.*, 2020), a stellar phenomena typically lasting for minutes to hours where the star becomes significantly brighter at shorter wavelengths, releasing large amounts of UV radiation and energetic particles.
If a flaring M dwarf has a terrestrial planet, the flare will induce significant changes in the planets atmospheric composition. If the planet has an earth-like atmosphere they may prevent the star from maintaining a significant ozone layer, raising the surface UV flux to potentially unsuitable levels for the development of life.
Previous work examining the impact of stellar flares on exoplanets (*Segura et al.*, 2010; *Venot et al.*, 2016; *Tilley et al.*, 2019) has mostly been performed in 1D, with 3D simulations only recently becoming available (*Chen et al.*, 2020). This work examines this question in 3D.

Unified Model & Atmospheric Chemistry

The Met Office Unified Model (UM) is a 3D general circulation model (GCM), and was developed to study and model Earth's climate. It has been adapted to model terrestrial exoplanets as well as hot Jupiters (*Drummond et al.*, 2016; *Boutle et al.*, 2017).
We have taken an aquaplanet with an earth-like atmosphere with the physical characteristics of Proxima Centauri (ProxCen) b. To model atmospheric chemistry, we are using a chemical kinetics scheme which is coupled to SOCRATES, the UM's radiative transfer scheme. The chemical kinetics scheme was tested with several networks comprising differing levels of complexity in the modelling of terrestrial ozone photochemistry, and can be seen in Figure 1:

- Chapman cycle and Dry Deposition
- Including HO_x (H, OH, HO_2) cycling
- Including NO_x (NO,NO_2,NO_3...) cycling (no emissions)

To study the impact of stellar energetic protons (SEPs) released during stellar flares on the planets chemistry, a quiescent profile of ion pair production in the atmosphere due to SEPs was assumed (approximating the stellar wind), taken from the averages of ion pair production data observed on Earth during 2009, around Solar minimum. Observations of ion pair production during strong solar storms are orders of magnitude higher than the quiescent conditions, so stellar flares are expected to produce an even larger impact on the ozone concentration.
Due to being tidally locked with a 11.2 day orbit, the planet has a very slow rotation rate, and is likely unable to sustain a geodynamo and any significant magnetic field. Without any magnetic field to deflect the SEPS, the entire dayside is subjected to the SEPs. The SEP induced ion pair production is used to determine the reaction rates for the following reactions:

$$H_2O + e^- \longrightarrow H + OH$$
$$N_2 + e^- \longrightarrow N(^4S) + N(^4S)$$
$$N_2 + e^- \longrightarrow N(^2D) + N(^2D)$$

These reactions either directly create additional HO_x constituents, or lead to the creation of NO, all of which will deplete ozone in the atmosphere.

Overview

- An area of current research is the impact of stellar flares on terrestrial planetary climates
- I have used the Met office Unified Model and a chemical kinetics scheme to study the impact of quiescent stellar winds in a 3D climate model
- Future work includes hi-rez surface spectra and modelling stellar flares

Planetary Description

ProxCen b is tidally locked (the same side of the planet faces the star at all times), which results in the planets atmospheric dynamics being significantly different than Earth's. This results in permanent gyres on the planets nightside, creating cold traps which provide a significant store of ozone.
Figure 1 plots the average dayside and nightside ozone profiles. The planets ozone layer lies within the stratosphere (> 15-20 km), and is severely depleted by the inclusion of additional species in the chemical network, as well as SEPs).
Figure 2 shows the ozone distribution throughout the planet The inclusion of SEPs causes a large decrease in the amount of ozone in the atmosphere. While the largest store of ozone is within the gyres, being on the nightside is insufficient to shield the ozone from the impact of SEPs.
The expected effect of including time-varying stellar flares is to further deplete the ozone layer and increase the UV reaching the surface, continuing to reduce the habitability of the planets surface.

Results 1: Vertical Ozone Profile

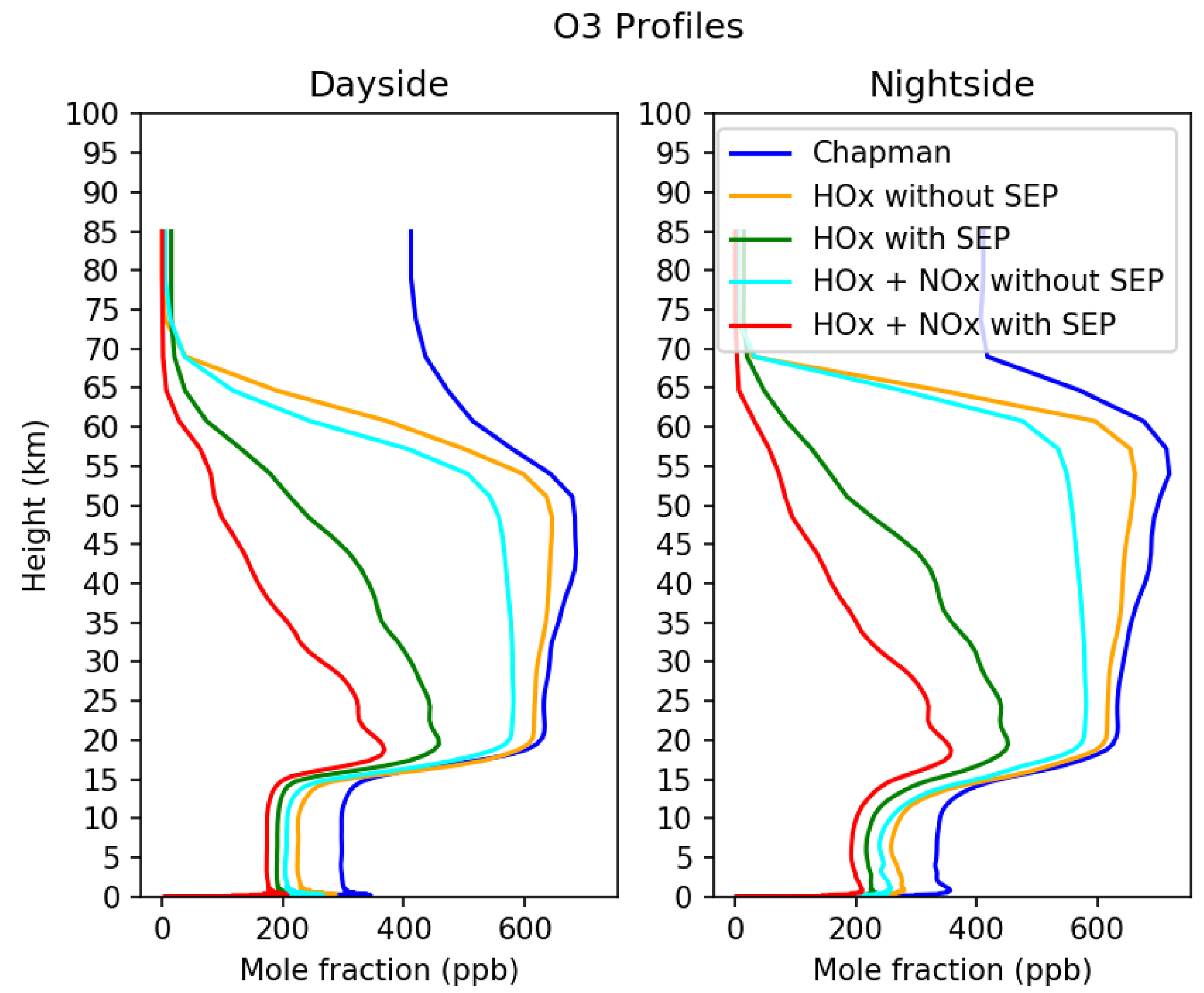

Figure 1: The average vertical dayside and nightside profile of ozone concentration.

Results 2: Ozone Distribution

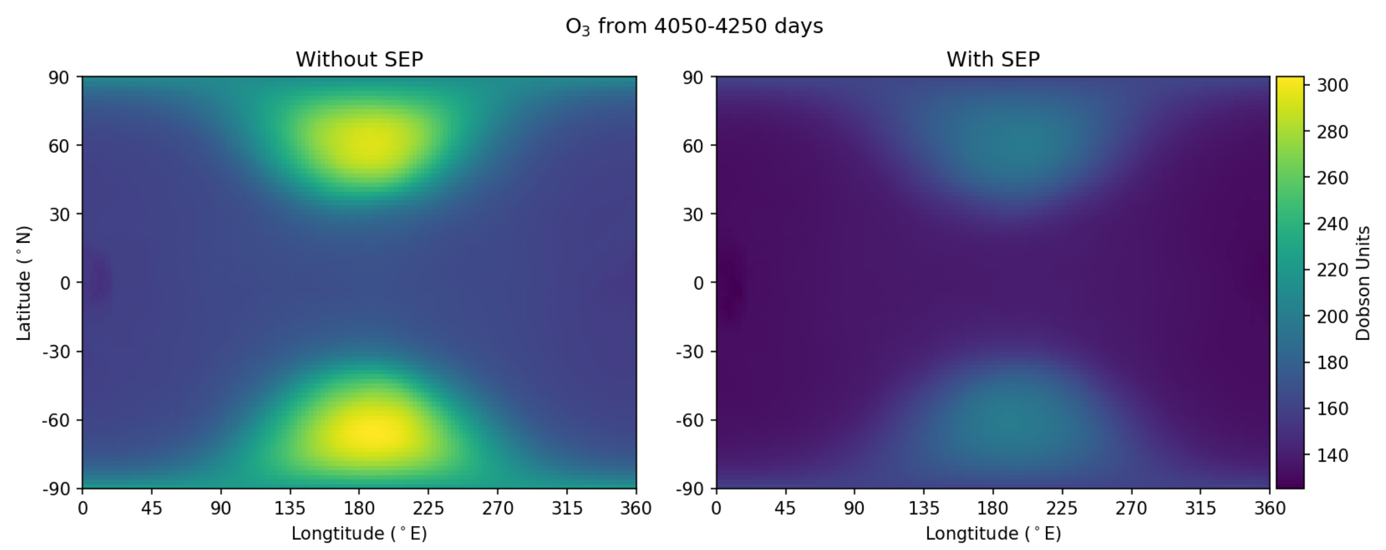

Figure 2: The global ozone distribution (each subfigure is centered on the antisubstellar point) for the complete chemical network (with or without SEPs) is shown in Dobson units. A Dobson unit is a measure for the column density of ozone ($\approx 2.69 \times 10^{20}$ molecules/m^2). The introduction of SEPs has caused a substantial drop in the amount of ozone globally, especially the nightside gyres.

Modelling Stellar Flares

Stellar flares consist of two components:

- A large increase in stellar UV radiation
- A Coronal Mass Ejection (CME)

It should be noted that not every flare will have an associated CME. It is also possible that the CME will not impact the planet. If a CME does impact the planet, the impact is expected to be large. Figure 3 contrasts the quiescent conditions assumed by this work, and extremes encountered during solar storms. While not lasting for long (as the eruption of particles is tied to the flare, and will cease when the flare ends), the larger ion pair production rate is expected to cause a large depletion of the planets ozone. This will be explored in future work.

Varying SEP Induced Ionisation Rates

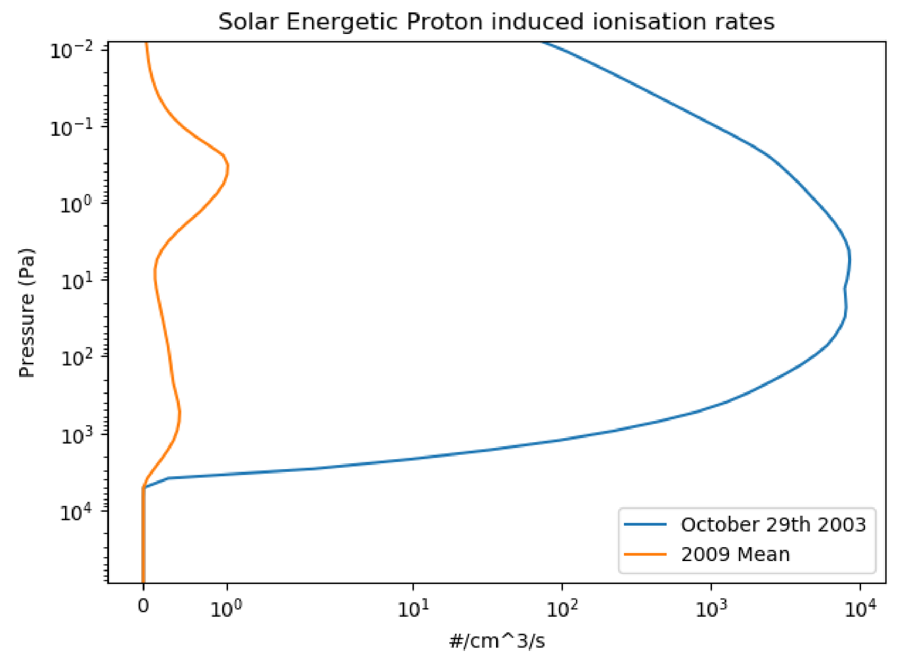

Figure 3: The ion pair production rate attributed to SEPs observed on Earth, an average of data from 2009 and data collected during the most energetic day of the Halloween 2003 solar storm. This is taken from the proton forcing data created for CMIP6 from *Matthes et al.* (2017).

Conclusions and Future Work

The UM has been used to simulate the effects of a quiescent stellar wind on the climate of a tidally locked terrestrial exoplanet orbiting Proxima Centauri with the intention of subjecting the planet to time-varying stellar flares with a range flare energies. We have established that even a quiescent stellar wind can cause a significant impact on the planets atmosphere.
Future work includes the implementation of stellar flares, allowing time-varying stellar spectra and SEP induced ionisation. Additionally, generating high resolution surface UV fluxes will allow us to look at the impacts of the flares to planetary habitability in high detail.

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