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, many exoplanets are known to orbit such stars. A large fraction of M dwarfs exhibit stellar flares (*Günther et al.*, 2020), a 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.

We have explored how the atmosphere of an Earth-like tidally locked planet orbiting an M dwarf responds to flares. If the planet has an earth-like atmosphere flares 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).

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 simulated an aquaplanet with an Earth-like atmosphere with the physical characteristics of Proxima Centauri (ProxCen) b (Figure 1 shows the stellar spectrum used in this work). To model the atmospheric chemistry, we are using a chemical kinetics scheme which is coupled to SOCRATES, the UM's radiative transfer scheme which handles photolysis. Figure 2 shows the atmospheric chemistry implemented in this work.

Stellar Spectrum

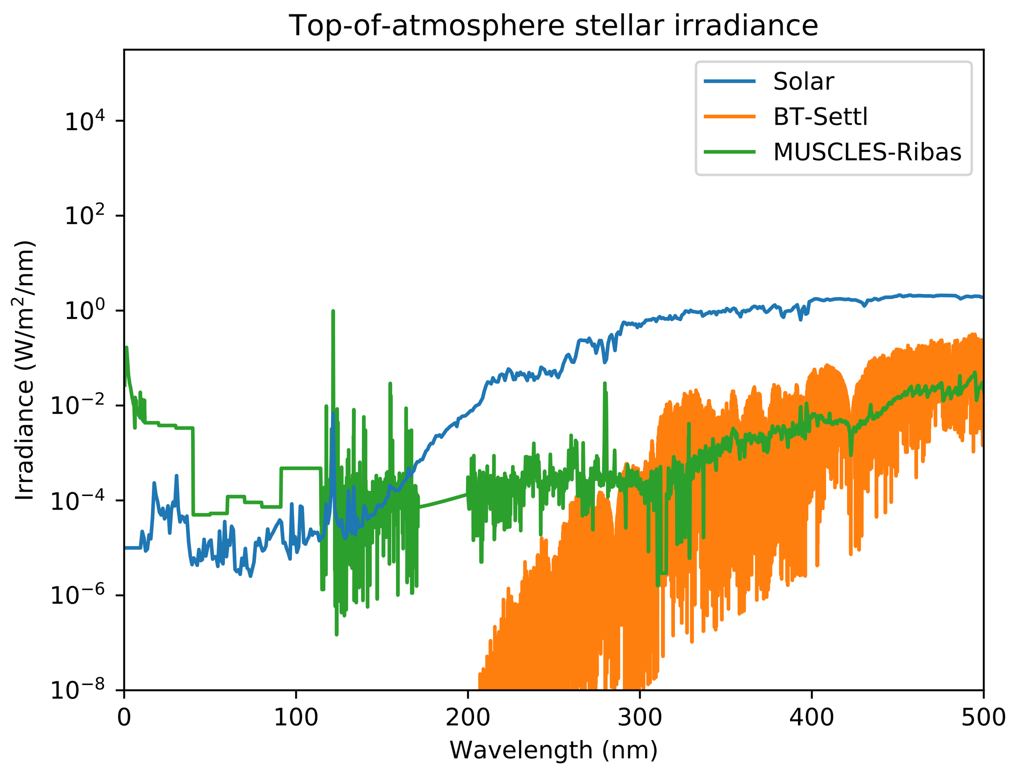

Figure 1: The top-of-atmosphere stellar spectrum used in this work (green), with the solar spectrum (blue) and an inactive stellar spectrum (orange) used in previous simulations of ProxCen b.

Modelling Stellar Flares

Stellar flares consist of two components:

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

A flare template from *Venot et al.* (2016) was used to describe the changes in stellar emission during a flare. We assume that a CME impacts the planet 6% of the time. CMEs are modelled using observations on Earth (used as part of CMIP6, *Matthes et al.*, 2017) and release large amounts of energetic particles which destroy water vapour and molecular nitrogen to create additional HO_x and NO_x molecules.

Overview

- An area of current research is the impact of stellar flares on terrestrial planetary climates
- The Met Office Unified Model and a chemical kinetics scheme is used to study the impact of stellar flares and coronal mass ejections on a planet in 3D
- A thin ozone layer is generated by the flares, surface UV shielding has increased

Chemical Network

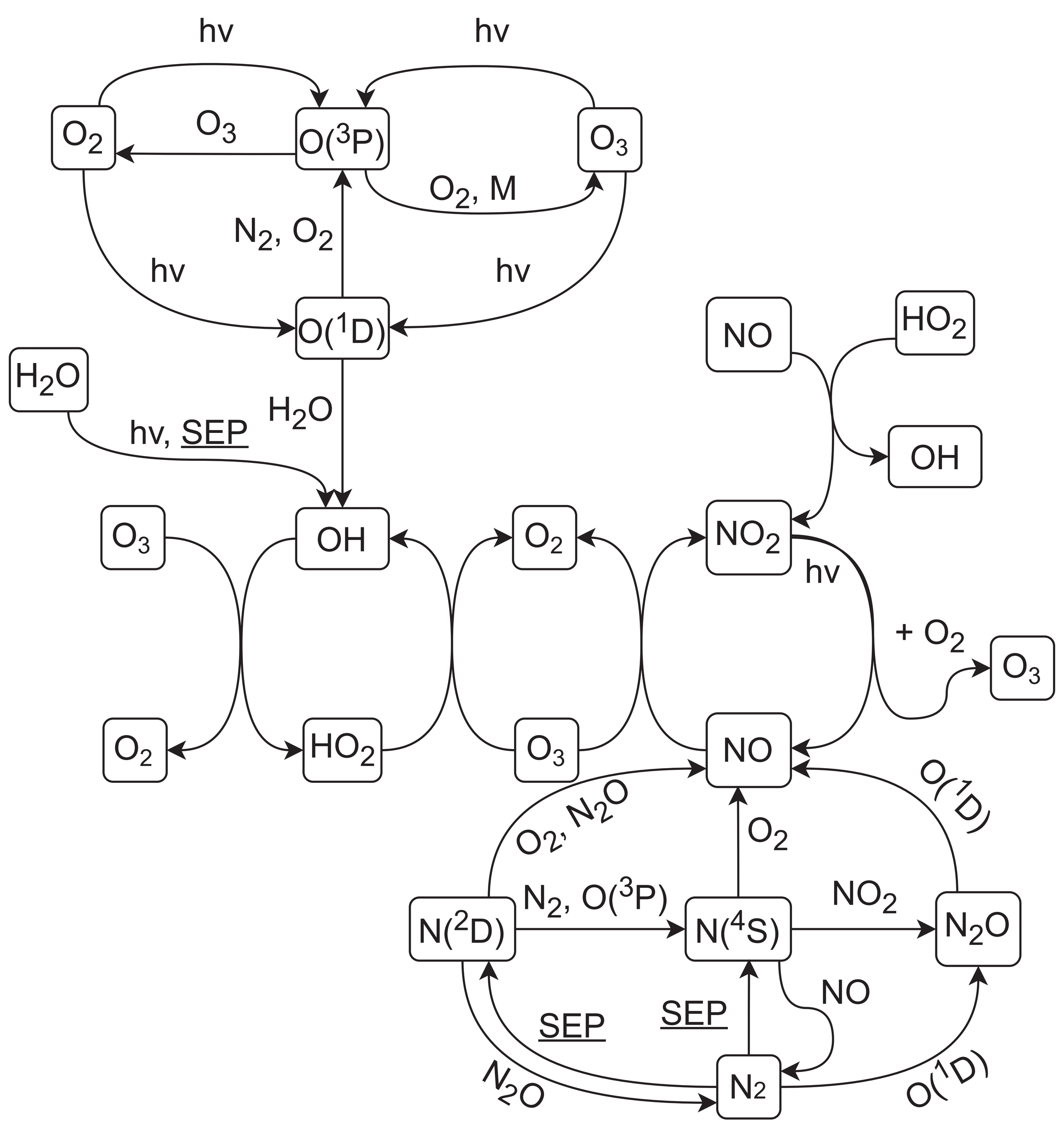

Figure 2: The main reaction pathways in this work.

Atmospheric Response to Flares

Flares cause the ozone column to increase from its quiescent state (Figure 3). This is sensitive to large flares, but settles towards a averaged ozone column of ~ 15 Dobson units (DU). The inclusion of CMEs causes little change in the global ozone column. The inclusion of CMEs is more visible in the hemispherically averaged vertical ozone profiles (Figure 4). Flares have created an ozone layer between 15-25 km and CMEs deplete ozone above 40 km. The increased amount of ozone improves the shielding of the surface from UV.

Figure 5 shows the surface UV (UV-A and UV-B) for the control, flares, and flares and CME simulations at the peak of the strongest flare included in this work. UV-A is relatively unchanged, but the amount of UV-B has decreased substantially. This is due to the increased amount of ozone that has been created by previous stellar flares.

Results 1: Ozone Column

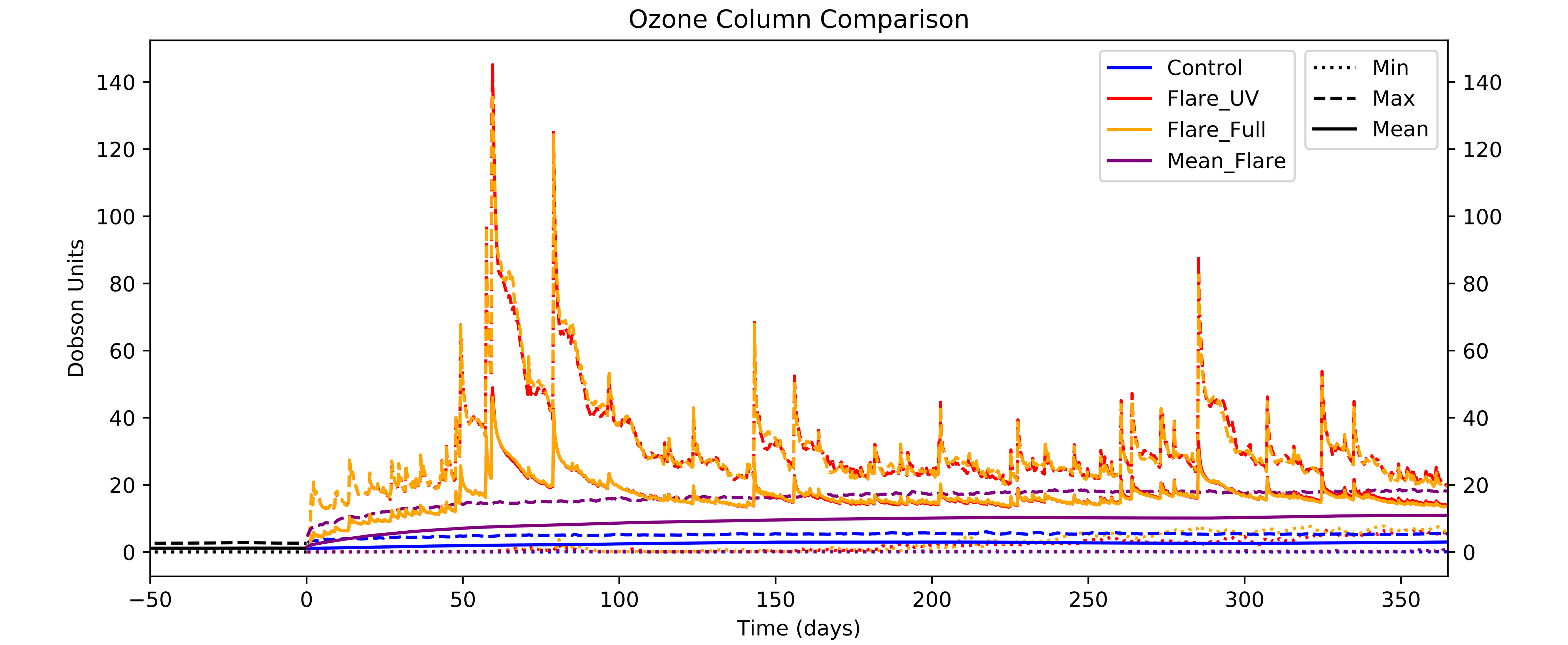

Figure 3: The globally averaged total ozone column from several simulations is shown in Dobson units. A Dobson unit is a measure for the column density of ozone ($\sim 2.69 \times 10^{20}$ molecules/m²).

Results 2: Vertical Ozone Profile

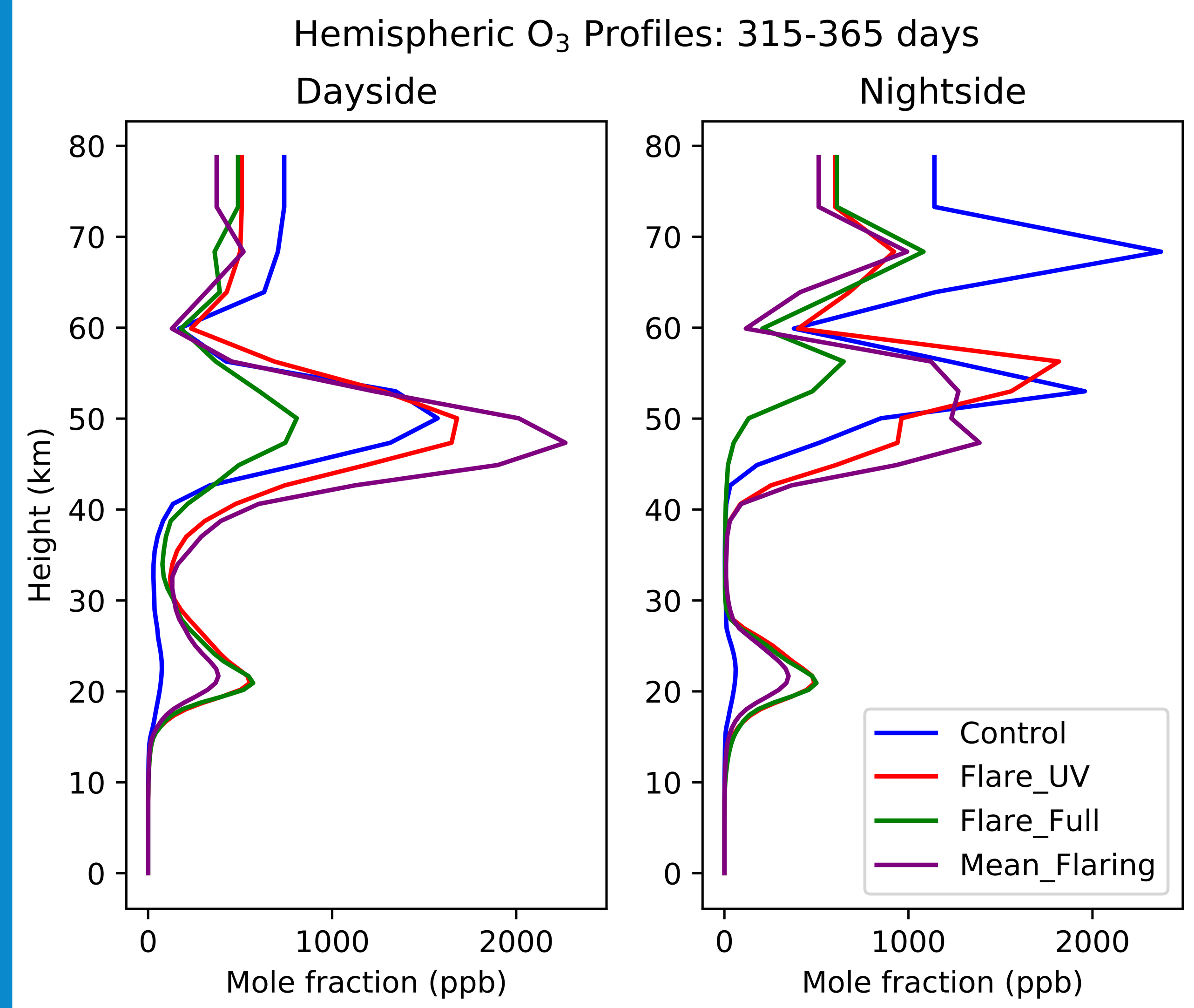

Figure 4: The spatially and temporally averaged vertical dayside and nightside profile of ozone concentration.

Conclusions and Future Work

- The impact of stellar flares and CMEs on a terrestrial planet has been simulated in 3D
- A thin ozone layer has been created
- UV shielding has increased

Future work includes the simulations of additional planets. The effects of flares on the evolution of early Earth is a currently open question, and the framework which has been developed provides a strong opportunity to explore that question.

Results 3: Surface UV Spectrum

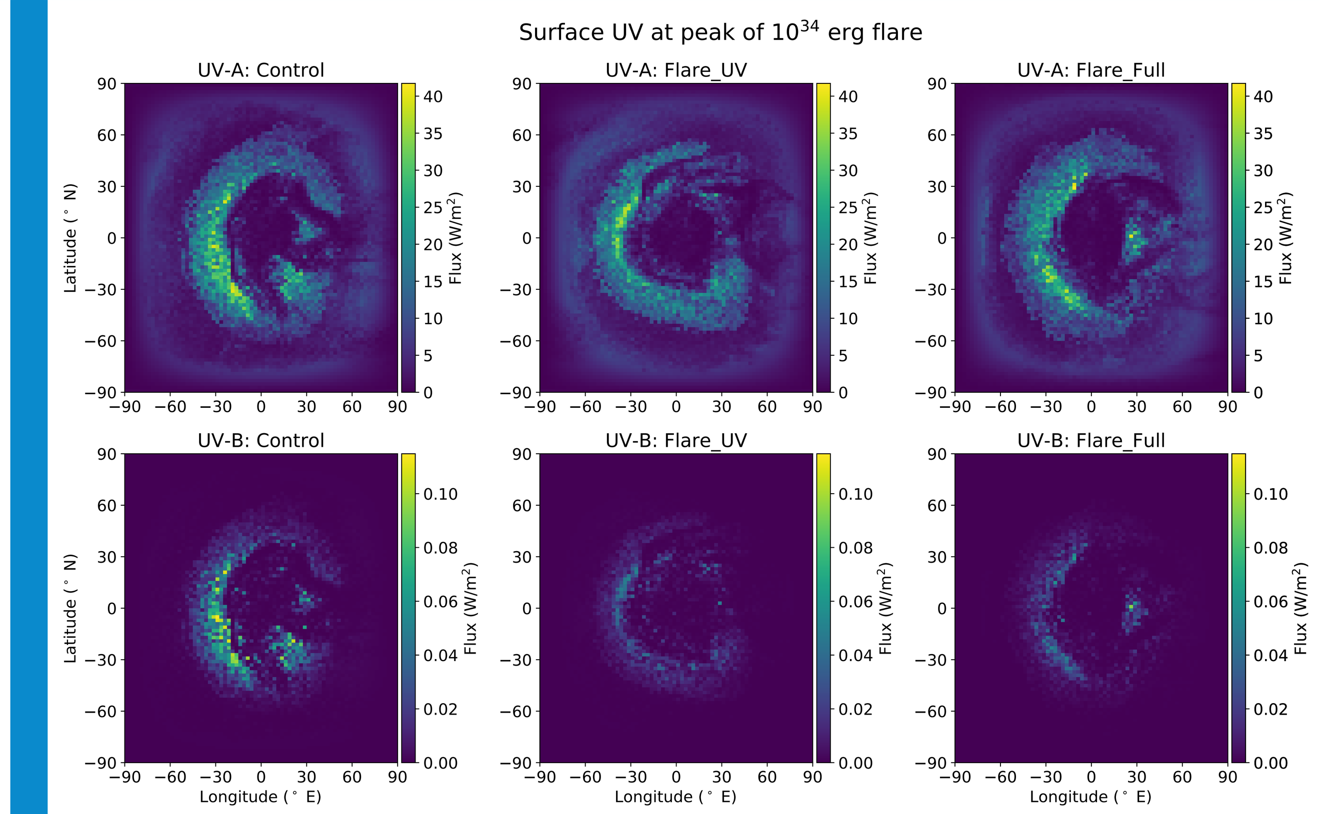

Figure 5: The day-side surface UV radiation environment during the strongest flare included in this work.

References

Boutle, I. A., N. J. Mayne, B. Drummond, J. Manners, J. Goyal, F. Hugo Lambert, D. M. Acreman, and P. D. Earnshaw, Exploring the climate of Proxima B with the Met Office Unified Model, *Astronomy & Astrophysics*, *601*, A120, doi:10.1051/0004-6361/201630020, 2017.

Chen, H., Z. Zhan, A. Youngblood, E. T. Wolf, A. D. Feinstein, and D. E. Horton, Persistence of flare-driven atmospheric chemistry on rocky habitable zone worlds, *Nature Astronomy*, doi:10.1038/s41550-020-01264-1, 2020.

Drummond, B., P. Tremblin, I. Baraffe, D. S. Amundsen, N. J. Mayne, O. Venot, and J. Goyal, The effects of consistent chemical kinetics calculations on the pressure-temperature profiles and emission spectra of hot Jupiters, *Astronomy & Astrophysics*, *594*, A69, doi:10.1051/0004-6361/201628799, 2016.

Günther, M. N., et al., Stellar Flares from the First TESS Data Release: Exploring a New Sample of M Dwarfs, *The Astronomical Journal*, *159*(2), 60, doi:10.3847/1538-3881/ab5d3a, 2020.

Matthes, K., et al., Solar forcing for CMIP6 (v3.2), *Geoscientific Model Development*, *10*(6), 2247–2302, doi:10.5194/gmd-10-2247-2017, 2017.

Segura, A., L. M. Walkowicz, V. Meadows, J. Kasting, and S. Hawley, The Effect of a Strong Stellar Flare on the Atmospheric Chemistry of an Earth-like Planet Orbiting an M Dwarf, *Astrobiology*, *10*(7), 751–771, doi:10.1089/ast.2009.0376, 2010.

Tilley, M. A., A. Segura, V. Meadows, S. Hawley, and J. Davenport, Modeling Repeated M Dwarf Flaring at an Earth-like Planet in the Habitable Zone: Atmospheric Effects for an Unmagnetized Planet, *Astrobiology*, *19*(1), 64–86, doi:10.1089/ast.2017.1794, 2019.

Venot, O., M. Rocchetto, S. Carl, A. R. Hashim, and L. Decin, INFLUENCE OF STELLAR FLARES ON THE CHEMICAL COMPOSITION OF EXOPLANETS AND SPECTRA, *The Astrophysical Journal*, *830*(2), 77, doi:10.3847/0004-637X/830/2/77, 2016.

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