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THE EFFECT OF UV RADIATION FROM FLARES ON THE OXYGEN CHEMYSTRY IN LOW O_2 ATMOSPHERES OF POTENTIALLY HABITABLE PLANETS AROUND M DWARFS

D. A. Ramos[1] and A. Segura[2]

RESUMEN

Las fulguraciones son emisiones repentinas de energía producidas en las atmósferas estelares. Las fulguraciones de estrellas M de la secuencia principal (enanas M) son más energéticas y frecuentes que las fulguraciones de estrellas similares al Sol. Estudiamos el efecto de la emisión de radiación UV (100-350 nm) de una fulguración en la química atmosférica de planetas en la zona habitable (HZ) de sus estrellas, en particular en el oxígeno (O_2) y ozono (O_3). El O_2 y O_3 son relevantes como bioseñales y protegen la vida de la radiación ultravioleta. Con un modelo fotoquímico acoplado a un modelo radiativo-convectivo se hicieron simulaciones del efecto de una fulguración en atmósferas similares a las del Proterozoico. Nuestros resultados muestran que la merma de O_3 más significativa es de 65% en atmósferas con 1% del nivel presente de O_2.

ABSTRACT

Flares are sudden emissions of energy produced in the stellar atmospheres. Flares produced by M main-sequence stars are more energetic and frequent compared to flares from Sun-like stars. Here, we focus on the effects of a flare UV emission (100-350 nm) in the atmospheric chemistry of planets in the habitable zone (HZ) of their stars, particularly on the oxygen (O_2) and ozone (O_3) column depths. O_2 and O_3 are relevant as biosignatures and to protect life from UV radiation. In the present work, We use the 1-D coupled radiative-convective and photochemical model to simulate the effect of a single flare on Proterozoic-like atmospheres in the HZ of M dwarfs. Our results show the most significant depletion of 65% for the O_3 column depth for an atmosphere composed of 1% of the present atmospheric level for O_2.

Key Words: habitable planets — M dwarf stars — planetary atmospheres — stellar flares

1. INTRODUCTION

The search for potentially habitable planets and life around other stars is a fundamental activity for astrobiology. The planets around M dwarfs may be good targets for the search for life. M Main Sequence stars lifetime is $\sim 10^{10}$ years at this stage, providing sufficient time for the emergence and evolution of life. The habitable zones of M dwarfs are closer to the star compared to Sun-like stars, which favors the possibility of detecting rocky planets with instruments already available. M dwarfs exhibit magnetic activity associated with their chromospheres; one manifestation of such activity are the unpredictable releases of energy or flares, the most active M dwarfs produce energy flares with energies $\sim 10^{34}$ ergs that occur once a month (Tilley et al. 2018)

The current strategy for the detection of life on exoplanets is based on the concept of biosignatures which is defined as the presence of a gas or other characteristic in a planetary spectrum that is indicative of a biological agent. On Earth, oxygen (O_2) and its photochemical product, ozone (O_3), are unequivocal evidence of life, since there are no abiotic processes capable of producing the amount of these compounds that are observed in the planet's atmosphere (Meadows et al. 2018).

The UV radiation emitted by M dwarfs drives photochemistry (Scalo et al. 2007; Tarter et al. 2007), and therefore, the atmospheric abundances of compounds that indicate habitability on Earth: N_2O (nitrous oxide), CH_4 (methane), and CH_3Cl (chloromethane), and the most relevant biosignatues O_2 and O_3. Previous simulations of Earth-like planets orbting in the habitable zone of an M dwarf star (Segura et al. 2005, 2010; Rugheimer et al. 2015) have shown that CH_4, N_2O and CH_3Cl have longer lifetimes than on Earth, and that the UV emitted by one energetic flare has not a significant effect in the ozone profile of the planet, therefore flares would not represent a danger to life on the surface of the planet (Segura et al. 2005, 2010).

[1]Facultad de Ciencias Espaciales, Universidad Nacional Autónoma de Honduras.
[2]Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México.

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2. METHODS: PLANETARY ATMOSPHERE SIMULATIONS

In the present work, we used the 1-D coupled radiative-convective and photochemical model used by Segura et al. (2010). The photochemical model solves for 55 different chemical species that are linked by 220 separate chemical reactions; The model was run with an initial timestep set to 10^{-4} s, with increasing time steps as the chemical species reaches equilibrium. To simulate the effect of a stellar flare on a planetary atmosphere, we started from a steady-state solution obtained as described by Segura et al. (2003, 2005), using the AD Leo spectrum during quiescence state. Once the steady solution was reached, the input stellar flux for wavelengths shorter than 440 nm was changed to that of the stellar flare at a given time. The flare time steps correspond to changes on the input stellar flux and vary depending on the time intervals between the available flare spectra. Given a flare time interval, the radiative-convective and photochemical model cross-communicate and synchronize the atmospheric temperature, and H_2O profiles and chemical variations for each timestep. The pressure layers calculated in the radiative-convective model were interpolated to the fixed altitude structure in the photochemical model, and then back, during the coupling procedure. The outputs of both models at the end of a given flare interval were used as initial conditions for the next time interval. Once the flare ended, the subsequent evolution of the atmosphere was tracked until it reached steady state. For more details, see Segura et al. (2010).

To study the effects of one stellar flare on a Proterozoic-like atmosphere, we selected the atmospheric abundance for O_2 (Reinhard et al. 2017), CO_2 (Kah & Riding 2007), and surface fluxes for CH_4 (Pavlov et al. 2003; Roberson et al. 2011), and N_2O (Buick 2007; Roberson et al. 2011). Boundary conditions for main compounds used in our simulations are listed in Table 1. All simulations were performed with a constant planetary surface pressure of 1 bar.

The Proterozoic Earth-like planet is located within the habitable zone of the M dwarf AD Leo at 0.16 au; that is the 1 au equivalent distance for AD Leo, the distance where the planet receives the same integrated energy from AD Leo as Earth does from the Sun (Segura et al. 2005). These models simulated the effect of a flare on the chemistry of atmospheres with low concentrations of O_2 of a planet in the habitable zone of an M dwarf star, that is, with atmospheric compositions similar to the Proterozoic eon.

TABLE 1

BOUNDARY CONDITIONS FOR COMPOUNDS IN THE PHOTOCHEMICAL MODEL

Compound	Boundary Condition	Value
O_2	Mixing ratio	1% - 10% PAL
CO_2	Mixing ratio	10 - 20 PAL
CH_3 Cl	Surface flux	5.78 Tg yr^{-1}
CH_4	Surface flux	320 - 5350 Tg yr^{-1}
N_2O	Surface flux	4 - 264 Tg yr^{-1}

PAL = Present Atmospheric Level

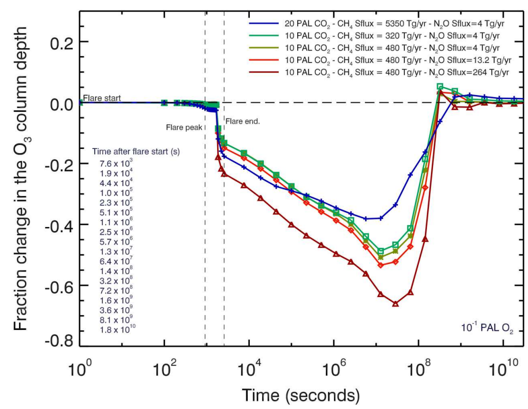

Fig. 1. The effects of a flare event on the O_3 column depth of a Proterozoic Earth atmosphere composed of 1% PAL O_2.

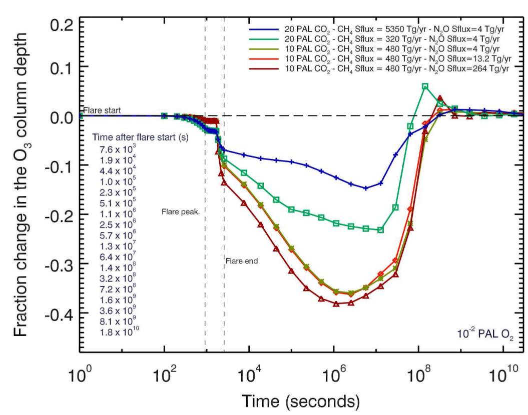

Fig. 2. The effects of a flare event on the O_3 column depth of a Proterozoic Earth atmosphere composed of 0.1% PAL O_2.

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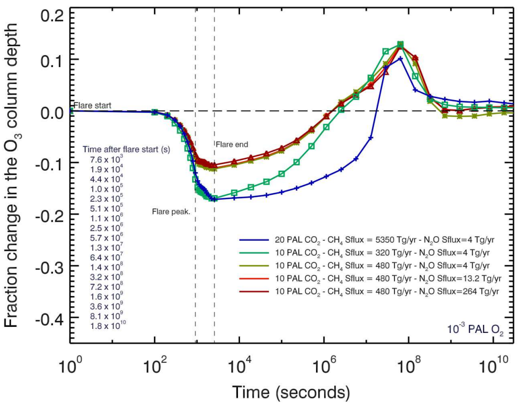

Fig. 3. The effects of a flare event on the O_3 column depth of a Proterozoic Earth atmosphere composed of 0.01% PAL O_2.

3. RESULTS

Figures 1-3 present the simulated effects of the flare on the atmosphere of a Proterozoic Earth-like planet orbiting an M dwarf with oxygen levels of 10^{-1}, 10^{-2}, and 10^{-3} PAL. The maximum O_3 column depletion is shown in Figure 1 for a planet with an atmospheric composition of 10^{-1} PAL O_2, 10 PAL CO_2, CH_4 surface flux = 480 Tg/ yr, and N_2O = 264 Tg/yr (red line/triangles).

The maximum change occurs at 2.9×10^7 s ($\sim$ 336 days) after the flare start with a reduction in the ozone column by 65%. In this depletion, the ozone column depth was 3.667×10^{18} cm^{-2}, approximately three times less than the initial value for the atmosphere. This is the result of the higher surface flux for N_2O; which reacts with $O(^1D)$ in the stratosphere, forming NO, promoting more destruction of O_3.

Simulations performed with lower concentrations of O_2 present intriguing features. Figures 2 and 3 show the ozone column depth for a planet with atmospheric oxygen levels of 10^{-2}, and 10^{-3} PAL. The magnitude of O_3 column depletion is reduced, particularly in the simulation with an atmosphere of 10^{-3} PAL O_2 (Figure 3) that shows a maximum of depletion of 16% (blue line/crosses). This may be the result of higher CO_2 atmospheric levels (20 PAL); CO_2 photodissociation rates occur more rapidly than O_2 photodissociation rates since these compounds absorb at the same wavelength, so less O_2 is photolyzed, CO_2 photolysis produces O, and this recombines, generating O_2 and O_3, and the atmosphere recovers in ($\sim$1 yr).

4. CONCLUSIONS

The results from all simulations suggest that the planetary atmosphere's response is sufficiently robust to high energy flares, preventing total O_3 loss, and allowing ozone column recovery to reach the steady-state equilibrium value in $\sim$ 300 years. Atmospheric levels of CH_4, N_2O are not altered significantly in either of the simulated atmospheres. The temperature profile for all simulations with low O_2 had maximum fluctuations of 5 K during the flare event and varying -3 to 8 K during the recovery phase compared from the initial equilibrium steady-state; these variations do not affect the habitability and the possibility of the planet to maintain liquid water on the surface.

The impact of UV radiation from M dwarfs leads to low O_3 concentrations in Proterozoic-like atmospheres (10% - 0.1% PAL O_2) that could last for decades. This could still produce a remarkable feature in the planet's MID-IR spectrum and be detectable by upcoming potentially habitable planet search missions. New simulations are being developed using recent atmospheric models to support and confirm these results.

REFERENCES

Buick, R. 2007, Geobiology, 5, 97
Kah, L. C.& Riding, R. 2007, The Geological Society of America, 799
Meadows, V. S., et al. 2018, AstBio, 18, 630
Pavlov, A. A., et al. 2003, Geology, 31, 87
Reinhard, C., et al. 2017, AstBio, 17, 287
Roberson, A. L., et al. 2011, Geobiology, 9, 313
Rugheimer, S., et al. 2015, ApJ, 809, 57
Scalo, J., et al. 2007, AstBio, 7, 85
Segura, A., et al. 2003, AstBio, 3, 689
Segura, A., et al. 2005, AstBio, 5, 706
Segura, A., et al. 2010, AstBio, 10, 751
Tarter, J.C., et al. 2007, AstBio, 7, 30
Tilley, M.A., et al. 2018, AstBio, 19, 64