“III Congreso Latinoamericano de Astrobiología (2021)”
Revista Mexicana de Astronomía y Astrofísica Serie de Conferencias (RMxAC), **55**, 50–52 (2023)

https://doi.org/10.22201/ia.14052059p.2023.55.12

III Latin American Congress of Astrobiology (3CLA)(Virtual-Modality, August 3-6, 2021)
Editors: Leticia Carigi, Sandra I. Ramírez Jiménez, Miguel Chávez Dagostino, and Millarca Valenzuela - DOI: https://doi.org/10.22201/ia.14052059p.2023.55.12

ATMOSPHERIC LOSS OF PLANETS AROUND M DWARF STARS DUE XUV RADIATION BY FLARES

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RESUMEN

La emisión de XUV (rayos X + UV extremo) de las fulguraciones de estrellas enanas M (0.08 − 0.6 $M_\odot$), ocasionalmente aumentan el flujo XUV en más de dos órdenes de magnitud por encima de niveles de reposo y puede impactar la habitabilidad de los planetas alrededor de estas estrellas. La radiación XUV puede calentar e ionizar la atmósfera superior de los planetas terrestres, lo que expande el radio del planeta y promueve la pérdida atmosférica. En este trabajo, estudiamos la contribución del flujo XUV debido a las fulguraciones en el escape atmosférico de planetas tipo Tierra alrededor de enanas M mediante simulaciones numéricas. Consideramos el primer Ga de planetas con abundancia de agua superficial inicial entre 1 y 10 océanos terrestres (TO), una envoltura de hidrógeno primordial ($\leq 10^{-3}$ $M_\oplus$), y con masas de estrellas del sistema entre 0.2 y 0.6 $M_\odot$. En este rango de parámetros, encontramos que las fulguraciones pueden eliminar hasta 2 TO más que las estrellas que no tienen fulguraciones, lo que, en algunos casos, se traduce en una duplicación de la pérdida total de agua. Estos resultados se obtuvieron agregando un nuevo módulo al código VPLanet.

ABSTRACT

The flare XUV (X rays + extreme UV) emission from M dwarf stars (0.08 – 0.6 $M_\odot$) occasionally increases the stellar XUV flux by more than two orders of magnitude above quiescent levels and can impact the habitability of planets around these stars. This wavelength range can warm and ionize the terrestrial planets’ upper atmospheres, which expands the planetary radius and promotes atmospheric loss. In this work, we study the contribution of the XUV flux due to flares on the atmospheric escape of Earth-like planets orbiting M dwarfs through numerical simulations. We considered the first Gyr of planets with initial surface water abundances between 1 and 10 terrestrial oceans (TO), a small primordial hydrogen envelope ($\leq 10^{-3}$ $M_\oplus$), and with host star masses between 0.2 and 0.6 $M_\odot$. In this parameter range, we find that flares can remove up to 2 TO more than non-flaring stars, which, in some cases, translates to a doubling of total water loss. These results were obtained by adding a new module for flares to the VPLanet software package.

Key Words: exoplanet atmospheres — habitable planets — star-planet interactions — stellar flares

1. INTRODUCTION

The habitability of planets orbiting M dwarf stars could be affected by the emission of XUV radiation (X-rays + ultraviolet, 0.1–100 nm; Ribas et al. (2005)) of these stars, which increases during flares by up to a factor of 100 above quiescent levels. This wavelength range warms and ionizes the upper atmosphere of Earth-like planets, expanding this atmospheric region and driving the atmospheric escape (Murray-Clay et al. 2009). When the atmosphere is in a moist or runaway greenhouse phase, the surface water reaches the stratosphere where it is photolized and hydrogen can reach the exosphere heated by XUV radiation and then escapes from the planet. Here, we consider ”Earth-like planets”, i.e. rocky planets with atmospheres, located in the habitable zone of their host star

The main goal of this work is to calculate the water loss of Earth-like planets in the main sequence habitable zones of M dwarf stars, due the influence of XUV radiation by flares. To realize this objective, we created and added a new module called FLARE (Amaral et al. submitted) inside the software package VPLanet (Barnes et al. 2020).

2. VPLANET

VPLanet is a package of physical models that is focused in planetary habitability, and is divided by modules that calculate the effect of different aspects of the habitability, i.e., tidal forces, planetary

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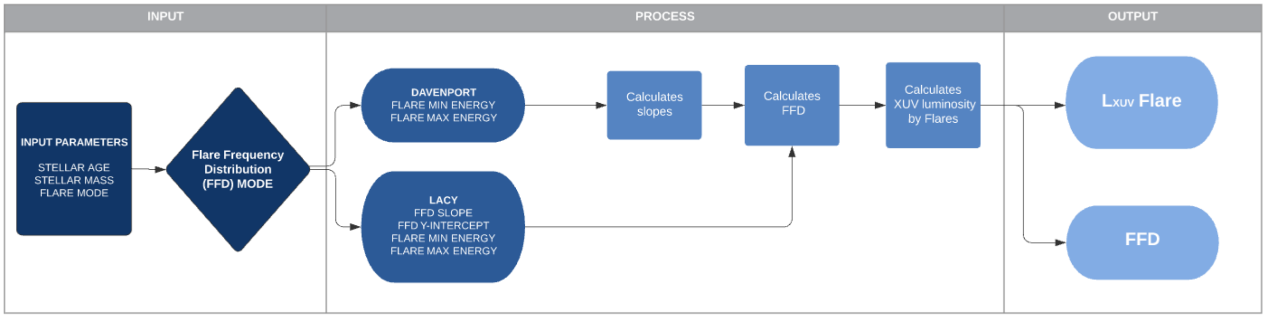

Fig. 1. Flowchart of FLARE module.

interior, atmospheric escape, stellar evolution, etc. In this work, besides the FLARE module, presented here, we also used the AtmEsc module, which calculates the atmospheric and water loss for the planet, and the STELLAR module, which calculates the evolution of the stellar parameters.

3. FLARE MODULE: MODEL DESCRIPTION

Our model calculates the XUV emitted by flares by using the flare frequency distribution (FFD) function from Lacy et al. (1976, Eq. 18):

$$log_{10}(\nu) = \alpha \; log_{10}(E_{Kepler}) + \beta, \qquad (1)$$

where ν is the flare rate for a given energy E_{Kepler}, which is the energy of the flare in the *Kepler* band pass, α is the FFD, and β is the FFD y-intercept.

The FLARE module has two modes, DAVENPORT and LACY, which are selected at runtime with the variable FFDmode (Figure 1). The first mode uses the Davenport et al. (2019) FFD, which changes as a function of stellar age and mass (Eq. 2 and 3 Davenport et al. 2019). The LACY mode uses a fixed FFD, where the parameters α and β are selected by the user.

Other parameters that can be selected by the user are the filter band for the input energies and, in the LACY mode, the FFD slope units. For any case a minimum and maximum flare energies must be defined, for this work we set the energy range between 10^{33} and 10^{36} ergs. After receiving this information, the code calculates the luminosity by flares (Figure 1), where both the DAVENPORT and LACY modes use the follow equation:

$$L_{XUV,f} = \int_{E_{min}}^{E_{max}} \nu(E_{XUV,f})dE. \qquad (2)$$

The XUV flux of all flares that occurred during a time step is added to the star's quiescent XUV luminosity, enabling a calculation of the total XUV flux that reaches the planet.

3.1. *DAVENPORT mode*

The DAVENPORT mode uses Eq. (1) to calculate the FFD in terms of flare energy, with a time- and mass-dependent α empirically derived from *Kepler* data (Davenport 2016; Davenport et al. 2019). This mode reproduces active stars with stellar masses between 0.25 and 0.75 $M_\odot$, and stellar flares with energies between 10^{32} and 10^{38} ergs (Davenport et al. 2019).

3.2. *LACY mode*

Similarly to the DAVENPORT mode, the LACY mode uses the same equation from Lacy et al. (1976) to calculate the FFD, but here the slope α of this equation remains constant over the stellar age. This mode is for the case when the user already has a specific FFD, then the user can set up the values of α and β, as well as the appropriate energy range.

4. RESULTS

We simulated scenarios considering planetary masses between 0.5 and 5 $M_\oplus$, with initial surface water between 1 and 10 terrestrial oceans (TO), around stars with masses between 0.2 and 0.6 $M_\odot$, over 1 Gyr.

For a planet with 1 $M_\oplus$ in a short runaway greenhouse phase, the results are hopeful. When these planets are around M dwarfs with masses less than 0.5 $M_\odot$, the maximum lost is up to 14%. For stellar masses above 0.5 $M_\odot$, the lost by flares is zero. This do not mean that these planets do not lose water, but that the water escape by flares is low. Indeed, the simulations show that these planets lost approximately 0.6 TO when we consider flares, as shown in Figure 2.

The full set of results show that flares can remove up to additional 2 TO of surface water when the planets are in a extended runaway greenhouse. Another feature is that flares increase the water escape in up to 63% more, compared to cases where

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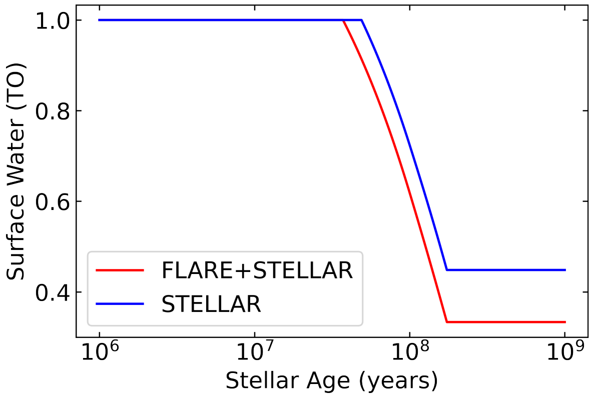

Fig. 2. Surface water content time evolution for a planet with 1 $M_\oplus$, starting its evolution with 1 TO of water in the surface around a 0.2 $M_\odot$ star.

just the quiescent XUV flux from the star is considered.

5. CONCLUSIONS

We simulated the XUV emission of M dwarf stars to estimate the atmospheric escape on synthetic planets (Amaral et al. submitted). For the simulations, we modeled a range of parameters, such as stellar mass, planetary mass, and initial water abundance, to estimate the trajectories that permit water on the planetary surfaces today, i.e. a habitable planet.

We added the Davenport et al. (2019) flare frequency distribution model to the VPLanet software package as a module we call FLARE. This module is now part of this open source project and available for community use at https://github.com/VirtualPlanetaryLaboratory/vplanet.

Acknowledgements: RB acknowledges support from NASA grants 80NSSC20K0229 and the NASA Virtual Planetary Laboratory Team through grant number 80NSSC18K0829. LA and AS acknowledge the support of UNAM DGAPA PAPIIT project IN110420. LA thanks CONACYT'S graduate scholarship program for its support. We thank David Fleming for developing the automatic mass loss functionality and Caitlyn Wilhelm for developing the vspace and multi-planet codes that facilitated our parameter sweeps. The authors would like to thank Alisson Youngblood and James Davenport, for the fruitful discussions and help with data.

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