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Modelling stellar proton event-induced particle radiation dose on close-in exoplanets

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ABSTRACT

Kepler observations have uncovered the existence of a large number of close-in exoplanets and serendipitously of stellar superflares with emissions several orders of magnitude higher than those observed on the Sun. The interaction between the two and their implications on planetary habitability are of great interest to the community. Stellar proton events (SPEs) interact with planetary atmospheres, generate secondary particles and increase the radiation dose on the surface. This effect is amplified for close-in exoplanets and can be a serious threat to potential planetary life. Monte Carlo simulations are used to model the SPE-induced particle radiation dose on the surface of such exoplanets. The results show a wide range of surface radiation doses on planets in close-in configurations with varying atmospheric column depths, magnetic moments and orbital radii. It can be concluded that for close-in exoplanets with sizable atmospheres and magnetospheres, the radiation dose contributed by stellar superflares may not be high enough to sterilize a planet (for life as we know it) but can result in frequent extinction level events. In light of recent reports, the interaction of hard-spectrum SPEs with the atmosphere of Proxima Centauri b is modelled and their implications on its habitability are discussed.

Key words: radiation mechanisms: non-thermal – planets and satellites: atmospheres – planets and satellites: magnetic fields – stars: flare.

1 INTRODUCTION

Kepler observations have revealed the existence of a large number of exoplanets orbiting in close-in configurations around a variety of stars. Due to proximity to the host star (∼0.01 au in some cases), such planets are greatly influenced by its activity, such as stellar wind, and abrupt emissions in form of coronal mass ejections (CMEs) and flares. Flares are often accompanied by bursts of energetic protons, also known as stellar proton events (SPEs). SPEs, CMEs and stellar wind directly interact with the exoplanet's atmosphere and are capable of enhancing atmospheric depletion (Vidotto et al. 2015) and photochemical reaction rates (Segura et al. 2005, 2010). These effects are especially relevant in case of M dwarfs, whose habitable zones are typically ∼0.1 au from the host star with high flaring activity. M dwarfs are faint, low-mass stars, with extremely long main-sequence lifetimes, and represent about 70 per cent of the total population of stars in the Milky Way. It has been shown that only 100 g cm^{-2} of CO_2 is required to support liquid water on the surface of tidally locked close-in planets around such stars (Haberle et al. 1996). A lot of effort has been made to model the effects of flares on climate and photochemistry of Earth-like planets in close-in orbits (Segura et al. 2005, 2010; Tabataba-Vakili et al. 2016). The studies of atmospheric changes resulting from stellar flares take into account the X-ray, extreme ultraviolet and proton flux from the host star. Because of their low energy (keV–MeV), stellar wind particles are not energetic enough to penetrate below the upper atmosphere, but 'hard' stellar protons (GeV) do have the capability.

There has been no study where the direct impact of SPE-induced charged particles on the exoplanet surface has been considered. The aim of this manuscript is to go beyond the impact of stellar flares on the atmosphere and model the production and propagation of secondary particles generated by SPEs interacting with the exoplanet atmosphere and calculate the radiation dose on its surface, and to better understand the role of planetary atmospheric size (column density), magnetic field and orbital distance from the host star on surface radiation dose and their implications on planetary habitability.

Protons with energies greater than the pion production threshold (290 MeV) produce secondary particles and initiate a cascade of particles with sufficiently energetic ones capable of reaching the planet's surface. On Earth, such events are called ground level enhancements (GLEs) and for exoplanets the equivalent term would be surface level enhancements. These high-energy stellar particles, with energies typically up to 10 GeV, contribute both to the

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atmospheric ionization and to the radiation dose on the surface and significant doses can potentially have biological implications (Ferrari & Szuszkiewicz 2009; Atri, Melott & Thomas 2010; Dartnell 2011; Melott & Thomas 2011; Atri, Hariharan & Grießmeier 2013; Atri & Melott 2011, 2014; Tabataba-Vakili et al. 2016). The flux of stellar particles increases by several orders of magnitude for time-scales of hours during intense SPEs, and becomes more important in case of close-in exoplanets. Hard-spectrum events are a subset of all SPEs emitted by a star. Soft-spectrum SPEs have significant effects in the upper atmosphere and do not produce GLEs, whereas hard-spectrum events produce GLEs with less effect in the upper atmosphere. Galactic cosmic rays (GCRs), which are of much higher energy but of lower flux, also contribute to the radiation dose on the surface of such planets (Atri et al. 2013; Grießmeier et al. 2016).

Even though there are numerous observations of stellar flares, the details of particle spectrum are difficult to determine, and the best approach is to model the effect of such events based on well-studied solar events. Flares with a fluence (at 1 au) of $<10^9$ protons cm^{-2} ($\sim 10^{31}$ erg) are recorded only a very few times per solar cycle on Earth (Smart et al. 2006). Events with higher fluence are less frequent, with the Carrington event (1859) with a fluence (at 1 au) of $\sim 10^{10}$ protons cm^{-2} ($\sim 10^{32}$ erg) occurring at a rate of about once a century. The AD 775 event had an estimated energy of $\sim 10^{33}$ erg. *Kepler* survey has observed a large number of energetic flares or superflares of energies 10^{33}–10^{36} erg around other stars (Maehara et al. 2012; Shibayama et al. 2013; Candelaresi et al. 2014). Studies have also shown that superflares on M stars are 10–100 times more frequent than on G stars (Maehara et al. 2012). It is the goal of the manuscript to quantify the surface radiation dose from hard-spectrum events on close-in exoplanets and discuss their implications on constraining planetary habitability.

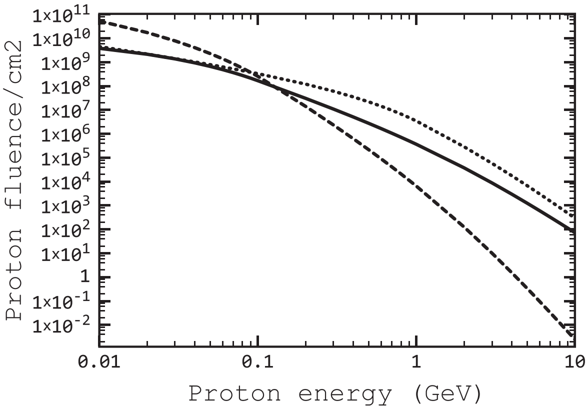

Figure 1. Event integrated spectra of the 1972 August 4 (dash), 1989 September 29 (solid) and 1956 February 23 (dots) SPEs on Earth, based on parameters obtained from Tylka & Dietrich (2009).

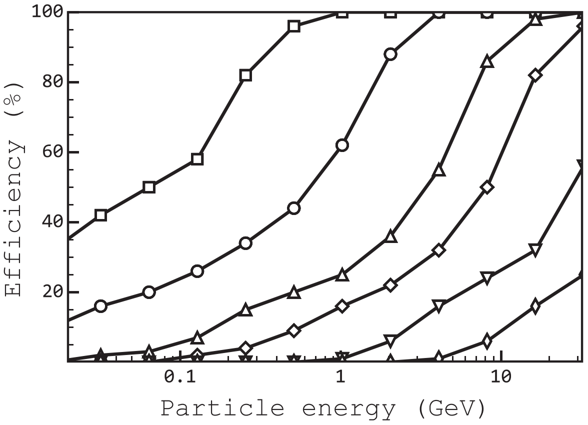

Figure 2. Efficiency of energetic protons penetrating with the magnetospheric filter function obtained from Grießmeier et al. (2015). 0.05 $\mathcal{M}_{\rm Earth}$ (same as 0) on the left-hand side represented by the squares, followed by 0.15, 0.5, 1.0, 3.0–10 $\mathcal{M}_{\rm Earth}$ all the way to the right-hand side represented by diamonds. All values of magnetic moment shown in the figure are relative to the Earth's magnetic moment.

2 NUMERICAL MODELLING

The radiation dose on the surface of the planet is governed by the flux and energy of incident particles, atmospheric depth and the strength of its magnetosphere. These effects are studied here by choosing well-studied SPEs with extensive GLE measurements on Earth and modelling its interactions with planetary atmospheres. Three such high-fluence events occurred on 1956 February 23 (SPE56), 1972 August 4 (SPE72) and 1989 September 29 (SPE89). The solar event spectra are represented by Band functions giving the event-integrated fluence for protons with energies between 10 MeV and 10 GeV (Tylka & Dietrich 2009). Fig. 1 shows the spectra of the three events. Events SPE56 and SPE72 represent the 'hard' and 'soft' spectra of large fluence events, respectively. The solar event SPE89 falls between the two, and, for reasons discussed later, will be the focus of this work. Since it occurred in the late 1980s, it is also one of the most well-studied high-fluence events accompanied with a GLE with both satellite- and ground-based observations.

Since incident charged particle flux strongly depends on the planetary magnetic field, the next step was to calculate the spectra of penetrating particles for different magnetic field configurations. In order to accomplish this, a magnetospheric filter function to calculate the energy-dependent shielding efficiency of planets with differing magnetic moments was needed. The magnetospheric filter function gives the efficiency of particles penetrating the atmosphere and is defined as the ratio of the number of shielded and unshielded particles ($n_{\rm shielded}/n_{\rm unshielded}$) (Grießmeier et al. 2015). The results of simulations from our earlier work were used and details of all the calculations can be found in the cited manuscript (Grießmeier et al. 2015). Fig. 2 is based on results from Grießmeier et al. (2015), and shows the efficiency of penetration of protons with increasing energies (from 10 MeV to 32 GeV) on planets with different magnetic field strengths (0.05 $\mathcal{M}_{\rm Earth}$ to 10 $\mathcal{M}_{\rm Earth}$) where 1 $\mathcal{M}_{\rm Earth} = 7.94\times 10^{22}$ A m^2. This filter function was used to calculate the input spectrum in each scenario for atmospheric modelling.

GEANT4 is a widely used Monte Carlo package that models the propagation of charged particles in planetary atmospheres and performs a variety of calculations such as computing radiation dose (Agostinelli et al. 2003). The code simulates particle interactions and tracks the particles down to the surface level defined by the user. In order to model SPE-induced radiation dose, simulations using the model with six atmospheric sizes of 30, 70, 100, 300, 700 and 1000 g cm^{-2} were performed and radiation doses at the surface level were computed. The Earth's present column density is 1036–1000 g cm^{-2}. The atmospheric interaction of SPEs was simulated by obtaining the input spectra using Band functions, by applying the magnetospheric filter functions described above and simulating 10^9 protons for each event from 10 MeV to 10 GeV, incident from different angles over the hemisphere. The magnetic field was switched off since the cut-off rigidities were taken from the magnetospheric filter functions. Although, the Earth's atmospheric

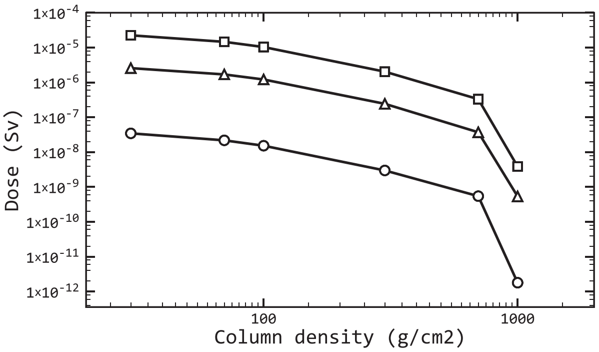

Figure 3. Radiation dose values from SPE56 (square), SPE89 (triangle) and SPE72 (circle) for various cases of atmospheric column depths at 1 au with 1 $\mathcal{M}_{\text{Earth}}$ magnetic moment.

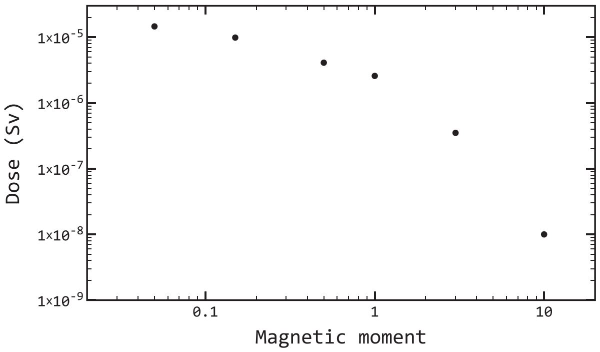

Figure 4. Radiation dose values as a function of changing planetary magnetic moment from SPE89 with 1000 g cm^{-2} atmosphere.

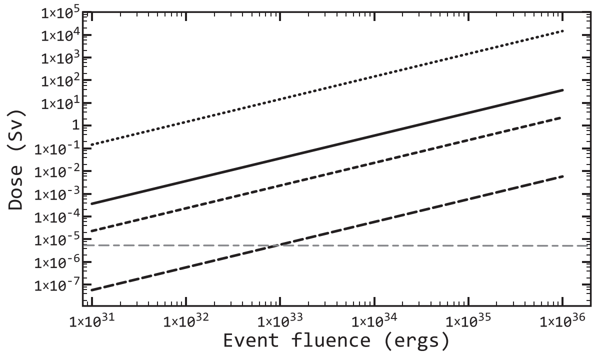

Figure 5. Radiation dose from SPEs at depths of 30 (dots) and 1000 g cm^{-2} (short dash) at 0.01 au, 30 (solid) and 1000 g cm^{-2} (long dash) at 0.2 au with 0.05 $\mathcal{M}_{\text{Earth}}$ magnetic moment. The globally averaged daily dose from natural background radiation on Earth is shown by a horizontal dashed line for comparison.

composition was used for this work, it must be emphasized that the calculations done here depend primarily on column density (g cm^{-2}) and are weakly dependent on the composition. The interactions modelled here depend on the number of nucleons per gram per centimetre, and the numbers are very similar for typical C, N and O atmospheres (12–16 g mol^{-1}). The calculations might change for a pure hydrogen atmosphere but this case will not be considered here. As explained later, the same event was used and further rescaled for the total energy between 10^{32} and 10^{36} erg to estimate the possible effects from a wide range of events such as superflares. These events were also rescaled to orbital distances of 0.01–0.2 au using the r^2 scaling factor since fluence $\sim(\theta_{\text{Opening}}\, R^2_{\text{Orbit}})^{-1}$. It must be noted that since these events occur on time-scales of hours, the GCR-induced dose during the period is much smaller than the high-fluence event-induced dose which is the focus of this work, and is likely going to decrease for close-in planets due to stellar wind shielding, and therefore will be ignored (Atri et al. 2013).

3 RESULTS

Fig. 3 shows the radiation dose values from SPEs 56, 72, and 89 for different cases of atmospheric column depths (30–1000 g cm^{-2}) with 1 $\mathcal{M}_{\text{Earth}}$ magnetic moment and 1 au orbital distance. As anticipated, the dose values drop significantly with increasing column depths for all three events. All three events displayed here are considered large events, but have significantly different dose depositions. This is because the dose depends both on the event fluence and on the spectral ‘hardness’. SPE72 has the highest fluence among the three events, but because of a ‘soft’ spectrum, the deposited dose is the smallest. SPE56 on the other hand has the largest dose among the three because of a ‘hard’ spectrum. SPE89 was therefore chosen for all calculations because it lies between the two extremes and would be a better representation of large events in general. In addition to the spectrum, column depth and fluence, another important factor governing the radiation dose is the planetary magnetic moment. Fig. 4 shows the variation of radiation dose from SPE89 with different planetary magnetic moments. There is about three orders of magnitude difference between the radiation doses from a 0.05 $\mathcal{M}_{\text{Earth}}$ to 10 $\mathcal{M}_{\text{Earth}}$ planet. The estimated event integrated proton fluence of SPE89 (>30 MeV) F_{30} is 1.4×10^9 protons cm^{-2} (Smart et al. 2006). The largest recorded solar event in history was the 1859 Carrington event with an estimated F_{30} of 1.1×10^{10} protons cm^{-2}. There have been observations of flares on stars with several orders of magnitude higher fluence than those observed on the Sun. Segura et al. (2010) simulated the atmospheric effects of an SPE with a fluence of 1.5×10^{12} protons cm^{-2}. The relationship between the event fluence and total energy (in erg) depends on a number of factors, for example the spectral hardness, opening angle of the event and the fraction of energy going into accelerating particles. In order to scale the total event energy with F_{30}, an assumption for F_{30} of $\sim 10^9$ protons cm^{-2} is made, and the total event energy is 10^{31} erg at 1 au. This assumption also makes sense since the $\sim 10^{10}$ protons cm^{-2} event described above had an estimated total energy of $\sim 10^{32}$ erg at 1 au. This relation will be used to scale the events up to 10^{36} erg.

Figs 5–7 show the radiation dose at depths of 30 and 1000 g cm^{-2}, at 0.2 and 0.01 au for planets with magnetic moments of 0.05, 1 and 10 $\mathcal{M}_{\text{Earth}}$, respectively. The case with 0.05 $\mathcal{M}_{\text{Earth}}$ is a planet with virtually no magnetic field and the radiation dose varies between 1.46×10^4 and 5.77×10^{-8} Sv. For comparison, the globally averaged annual dose from natural background radiation on Earth is 2.4 mSv (Atri & Melott 2014) which equates to 6.6×10^{-6} Sv d^{-1}. The most extreme dose, as expected, is for a non-magnetized planet with a thin atmosphere. This case is also important because most non-magnetized planets will eventually lose their atmospheres due to the impact of stellar wind. This effect would be amplified in close-in scenarios. Fig. 6 shows the radiation dose for a planet with 1 $\mathcal{M}_{\text{Earth}}$ and the dose lies between 2.57×10^3 and 1.34×10^{-8} Sv. The individual doses fall with increasing magnetic shielding and this effect is most amplified with 10 $\mathcal{M}_{\text{Earth}}$ magnetic moment where the dose varies between 10 and 1.59×10^{-5} Sv.

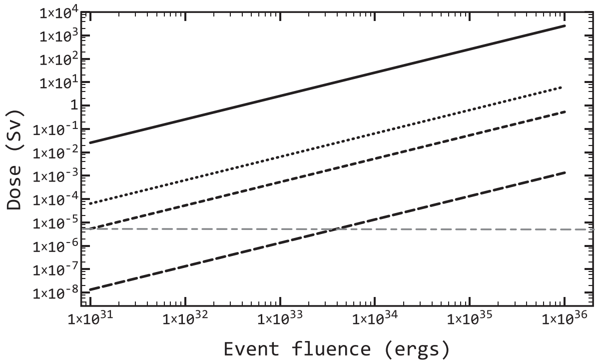

Figure 6. Radiation dose from SPEs at depths of 30 (solid) and 1000 g cm^{-2} (short dash) at 0.01 au, and 30 (dots) and 1000 g cm^{-2} (long dash) at 0.2 au with 1 $\mathcal{M}_{\rm Earth}$ magnetic moment. The globally averaged daily dose from natural background radiation on Earth is shown by the horizontal dashed line for comparison.

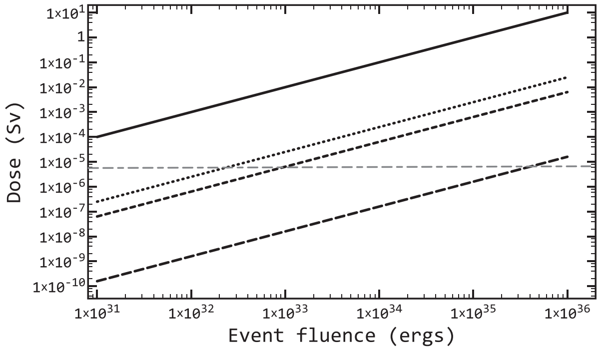

Figure 7. Radiation dose from SPEs at depths of 30 (solid) and 1000 g cm^{-2} (short dash) at 0.01 au, 30 (dots) and 1000 (long dash) g cm^{-2} at 0.2 au with 10 $\mathcal{M}_{\rm Earth}$ magnetic moment. The globally averaged daily dose from natural background radiation on Earth is shown by the horizontal dashed line for comparison.

3.1 Radiation dose on Proxima Centauri b

Proxima Centauri b is a recently discovered exoplanet orbiting our stellar neighbour Proxima Centauri (1.3 pc), an M dwarf (Anglada-Escudé et al. 2016). Even though its atmosphere is yet to be characterized, preliminary analysis suggests that because of its proximity to the host star (∼0.05 au) it receives about 65 per cent of the energy that Earth receives from the Sun, and the planet might be ‘habitable’ with reasonable assumptions about its atmosphere. But would a potential ecosystem on the planet be able to survive hard-spectrum superflares? SPE56 is a good proxy for such events as discussed above and was applied to possible atmospheric column densities on Proxima b assuming Earth-equivalent planetary magnetic field. Fig. 8 shows that if it has a 1000 g cm^{-2} atmosphere (like the Earth) and 1 $\mathcal{M}_{\rm Earth}$ magnetic moment, the particle radiation dose from even the most extreme SPE would not have any significant impact on its biosphere. However, for thinner atmospheres (700 g cm^{-2} or lower, as shown in the figure) it would be able to produce ‘extinction level’ doses (5–10 Sv) although not enough to sterilize the planet of life as we know it (∼10^5 Sv; Harrison & Anderson 1996). The dose would also increase considerably if the magnetic moment is much lower in case the planet is tidally locked (Grießmeier et al. 2015). A detailed analysis on Proxima b will be reported in a forthcoming manuscript by the author.

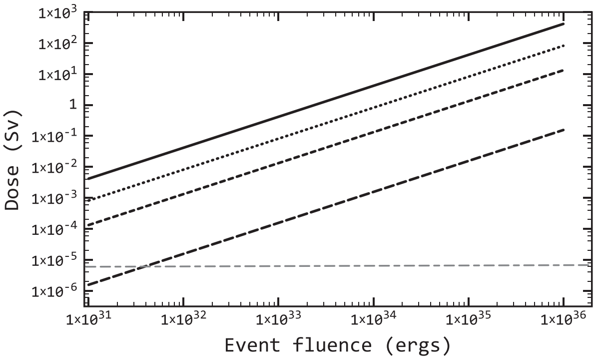

Figure 8. Radiation dose from hard-spectrum SPEs (SPE56 spectrum) at depths of 100 (solid), 300 (dots), 700 (short dash), 1000 g cm^{-2} (long dash) at for Proxima Centauri b with 1 $\mathcal{M}_{\rm Earth}$ magnetic moment. The globally averaged daily dose from natural background radiation on Earth is shown by the horizontal dashed line for comparison.

4 DISCUSSION

The results show a wide range of surface radiation doses on planets in close-in configurations with varying atmospheric column depths, magnetic moments and orbital radii. The critical importance of both the planetary magnetic field and size of the atmosphere in maintaining a low radiation dose environment has been demonstrated, even in the case of extreme events such as superflares. The overall effect of radiation dose would be from the cumulative effect of multiple SPE events and depends on a combination of flare energy and frequency in a particular star system. M dwarfs are very active and have the highest flare frequency, followed by K- and G-type stars like the Sun (Hawley et al. 2014). On M dwarfs, the superflare frequency in the 10^{34}–10^{35} erg range is about once a decade, 10^{33} erg flares occur once every 100 d and 10^{32} erg flares occur about once every 5 d (Maehara et al. 2012; Hawley et al. 2014). In general, large superflares are more frequent by a factor of 20 on M and 6 on K-type stars compared to G-type stars (Shibayama et al. 2013). The occurrence frequency of superflares can be fitted with a power law which is ∼−1.6 for M, ∼−1.7 for K and much steeper ∼−2.2 for G-type stars (Maehara et al. 2012). Statistical analysis of superflares has indicated that 10^{34}–10^{35} erg superflares can occur once every 800–5000 yr on a Sun-like star (Maehara et al. 2012; Shibata et al. 2013; Shibayama et al. 2013). Young and fast-rotating stars are expected to have such flares with higher intensity and frequency consistent with dynamo theory; however, not all superflare stars fit these criteria (Wichmann et al. 2014). Some suggest that superflares could occur on stars with relatively low activity levels too (Candelaresi et al. 2014). More observations will give us a better picture of the rate of occurrence of these events and would help in better estimating the threat to potential planetary life in such systems.

Based on the results of radiation exposure experiments, it is seen that organisms are resistant to a wide range of radiation doses, ranging from a few Sv to ∼10^5 Sv. A radiation dose of 50 mSv and beyond is considered harmful for humans and can cause mutations and lead to carcinogenic effects. A dose of 1 Sv causes radiation sickness in humans and higher doses can cause death. Primitive microorganisms (i.e. *Escherichia coli*) are generally more radiation resistant than modern animals (i.e. mammals). Lethal radiation doses are estimated to be 5–10 Sv for humans, 6–10 Sv for small mammals, 100 Sv for goldfish, 150 Sv for bats, 100–1000 Sv for insects, 10^4 Sv for viruses, and 10^4–10^5 Sv for *Deinococcus radiodurans* (Harrison & Anderson 1996). Such high radiation doses on a planet can limit the type of organisms that could survive in such conditions. For example, a dose of 1000 Sv would eliminate all mammals, birds and insects and would leave the planet with more primitive life forms such as viruses, *Deinococcus radiodurans* and other extremophiles. A dose above 10^5 Sv would practically sterilize the planet and leave it uninhabitable to life as we know it. None of the cases considered here lead to such high radiation dose.

Based on the simulation results, it can be concluded that for close-in exoplanets with sizable atmospheres and magnetospheres, the radiation dose contributed by stellar superflares is not enough to sterilize a planet (for life as we know it) but can result in frequent extinction level events shaping the evolution of potential ecosystems on such exoplanets. These results are especially important for exoplanets around low-mass stars such as M dwarfs whose habitable zones lie in close-in configurations.

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