Stellar flares versus luminosity: XUV-induced atmospheric escape and planetary habitability

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Accepted 2020 September 9. Received 2020 September 3; in original form 2020 April 28

ABSTRACT

Space weather plays an important role in the evolution of planetary atmospheres. Observations have shown that stellar flares emit energy in a wide energy range ($10^{30} – 10^{38}$ erg), a fraction of which lies in X-rays and extreme ultraviolet (XUV). These flares heat the upper atmosphere of a planet, leading to increased escape rates, and can result in atmospheric erosion over a period of time. Observations also suggest that primordial terrestrial planets can accrete voluminous H/He envelopes. Stellar radiation can erode these protooatmospheres over time, and the extent of this erosion has implications for the planet’s habitability. We use the energy-limited equation to calculate hydrodynamic escape rates from these protooatmospheres irradiated by XUV stellar flares and luminosity. We use the flare frequency distribution of 492 FGKM stars observed with TESS to estimate atmospheric loss in habitable zone planets. We find that for most stars, luminosity-induced escape is the main loss mechanism, with a minor contribution from flares. However, flares dominate the loss mechanism of $\sim 20$ per cent M4–M10 stars. M0–M4 stars are most likely to completely erode both their proto- and secondary atmospheres, and M4–M10 are least likely to erode secondary atmospheres. We discuss the implications of these results on planetary habitability.

Key words: stars: flare – planets and satellites: atmospheres – astrobiology – hydrodynamics – radiation mechanisms: thermal – planets and satellites: terrestrial planets.

1 INTRODUCTION

Planetary habitability is one of the most important concepts in exoplanet science. It is defined as the zone around a star in which a planet is able to sustain liquid water on its surface (Kasting, Whitmire & Reynolds 1993). While this approach is useful to identify potentially habitable planets around stars, it fails to take into account the damaging aspect of stellar activity on such planets. Stellar radiation in space weather events includes stellar flares, Coronal Mass Ejections, and Stellar Proton Events, which emit energy in high-energy regimes of extreme ultraviolet (XUV) (10–120 eV) photons and charged particles (10 MeV–10 GeV) (Tylka & Dietrich 2009). Space weather-induced effects include planetary atmospheric losses (Gronoff et al. 2020), photochemistry (Gronoff et al. 2020), photochemistry (Tilley et al. 2019), as well as photochemical- and plasma-induced escape (e.g. Gronoff et al. 2020, and references therein). However, studies have shown that thermal hydrodynamic escape is likely dominant in cases where a large amount of XUV energy is deposited (e.g. Luger et al. 2015). Atmospheric escape can be estimated based on the total amount of heat deposited in the atmosphere, which is proportional to the XUV energy emitted from a star in steady-state or during a flare; e.g. via the energy-limited escape formula (Watson, Donahue & Walker 1981). Observations from Kepler, Gaia, and TESS have shown that active stars can emit energy in the $10^{30} – 10^{38}$ erg energy range (Maehara et al. 2012; Notsu et al. 2019; Günther et al. 2020), a fraction of which is emitted in XUV. According to the flare frequency distribution (FFD) obtained from observations, the higher-energy flares, which can cause more damage, are rare, and the less effective lower-energy flares are more frequent. On long time-scales, the atmospheric loss from flares will cumulatively lead to the erosion of the atmosphere, which can be estimated by using FFD obtained from observations. Kepler observations have shown that a large fraction of low-mass terrestrial planets have large H/He envelopes (Owen & Mohanty 2016). It is believed that they accrete large H/He envelopes in early stages of their lives that can be eroded with time due to stellar radiation. Wolfgang & Lopez (2015) estimated this primordial atmospheric mass as $\sim 1$ per cent of the mass of the planet. If these protooatmospheres can be completely stripped away, they can be replaced by secondary atmospheres, like we see in Solar system terrestrial planets (e.g. Kopparapu et al. 2013, 2014). Calculating the rate of atmospheric escape is therefore crucial in determining atmospheric structure and composition, which in turn has implications on planetary habitability. We focus our effort on recent data from TESS (Günther et al. 2020), which has given us the FFD of

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492 FGKM stars. The main goal of this paper is to understand how stellar luminosity and flares can lead to atmospheric escape on HZ planets on long time-scales and how these losses impact planetary habitability.

2 METHOD

We obtain FFD from a sample of 492 FGKM stars observed with TESS (Günther et al. 2020), consisting of 128 M4–M10 stars, 233 M0–M4 stars, and 131 FGK stars. Each star has its own best-fitting parameters α and β derived from observations and we use these values to extrapolate FFD between 10^{30} and 10^{38} erg:

$$\log_{10}(\nu_{\text{flare}}) = \alpha \log_{10}(E_{\text{bol}}) + \beta.$$  

Here, $E_{\text{bol}}$ is the total bolometric energy of the flare and $\nu_{\text{flare}}$ is the flare rate, which can also be expressed as

$$\nu_{\text{flare}} = 10^\beta E_{\text{bol}}^\alpha.$$  

We use this expression to calculate the occurrence rate of flares in this energy range over time-scales of interest.

Next we use the catalogue data to calculate star–planet distance by determining their HZs using the following method. All 492 of these stars have an effective temperature ($T_{\text{eff}}$) derived in the data; however, only 485 stars have a derived effective radius ($R_{\text{eff}}$). For those seven stars with only $T_{\text{eff}}$ available, as done by Günther et al. (2020), $R_{\text{eff}}$ is interpolated from the values given in Pecaut & Mamajek (2013).

A star’s bolometric luminosity ($L_{\text{bol}}$) is then calculated according to its $T_{\text{eff}}$ and $R_{\text{eff}}$:

$$L_{\text{bol}} = 4\pi R_{\text{eff}}^2 \sigma T_{\text{eff}}^4,$$  

where $\sigma$ is the Stefan–Boltzmann constant. The star’s $T_{\text{eff}}$, $R_{\text{eff}}$, and $L_{\text{bol}}$ are then used to determine its six HZs limits (Kopparapu et al. 2013, 2014): (1) Recent Venus, (2) Early Mars, (3) Runaway Greenhouse, and (4) Maximum Greenhouse for 1 $M_\oplus$; and Runaway Greenhouse for (5) 5 $M_\oplus$ and (6) 0.1 $M_\oplus$. Finally, the HZs in distance from the host star ($d_{\text{HZ}}$) are calculated as

$$d_{\text{HZ}} = \sqrt{\frac{L_{\text{bol}}/L_\odot}{S_{\text{eff}}}} \text{[au]},$$  

where $L_\odot$ is the stellar luminosity and $S_{\text{eff}}$ is the effective stellar flux in the star’s HZ.

From a star’s bolometric energy, we can calculate the amount of XUV energy incident on top of a planetary atmosphere ($F_{\text{XUV,flare}}$) at the six $d_{\text{HZ}}$:

$$F_{\text{XUV,flare}} = \frac{f_{\text{XUV}} E_{\text{bol}}}{4\pi d_{\text{HZ}}^2},$$  

where $f_{\text{XUV}}$ is the estimated fraction of the total bolometric energy emitted in XUV. Since $f_{\text{XUV}}$ depends on the spectral hardness, which can be ~0.2 for hard-spectrum events (Woods et al. 2004), and lower for soft-spectrum ones, we set it to 0.1 for all our events. After applying the star’s FFD from equation (2) and integrating over the entire energy range of 10^{30}–10^{38} erg, we calculate the mass losses at the six HZs via the energy-limited formulation:

$$M_{\text{loss,flare}} = \sum_{10^{30}}^{10^{38}} \frac{\eta \pi R_{\text{XUV}}^2 F_{\text{XUV,flare}}}{GM_P/R_P}. $$  

Here, $\eta$ is the heating efficiency of the atmosphere; $G$ is the gravitational constant; $M_P$ is mass of the planet; $R_P$ and $R_{\text{XUV}}$ are the radius of the planet and the atmosphere’s effective radius, respectively; and $\pi R_{\text{XUV}}^2$ is the planetary envelope cross-section on to which the incident energy is absorbed. We further simplify this calculation by assuming $R_{\text{XUV}} \sim R_\oplus$:

$$M_{\text{loss,flare}} = \sum_{10^{30}}^{10^{38}} \frac{\eta \pi R_{\text{XUV}}^2 F_{\text{XUV,flare}}}{GM_P/R_P}.$$  

$$= \sum_{10^{30}}^{10^{38}} \frac{\eta f_{\text{XUV}} R_P^3}{4d_{\text{HZ}}^2 GM_P} 10^\beta E_{\text{bol}}^\alpha.$$  

A range of values of heating efficiencies have been applied in literature, from as high as 100 per cent to as low as 10 per cent (Shematovich, Ionov & Lammer 2014, and references therein). We use a value of 10 per cent for our calculations based on the results of detailed modelling conducted by Shematovich et al. (2014), where it was concluded that values between 10 and 15 per cent would lead to accurate results. However, since we assume $R_{\text{XUV}} \sim R_\oplus$, even with a low heating efficiency our mass-loss results may still be an underestimation. We apply equation (10) to four terrestrial planets on long time-scales and how these losses impact planetary habitability.

3 RESULTS

There is a large variation in the cumulative energy released from flares among the sample of 492 stars. Our calculations show that the total...
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Figure 1. Total energy released by flares over 100 Myr corresponding to the flare’s bolometric energy and frequency for FGK stars. Here, the bolometric energy range is represented in red ($10^{30}$ erg), blue ($10^{31}$ erg), green ($10^{32}$ erg), magenta ($10^{33}$ erg), orange ($10^{34}$ erg), cyan ($10^{35}$ erg), pink ($10^{36}$ erg), grey ($10^{37}$ erg), and lawn green ($10^{38}$ erg).

Figure 2. Flare-induced losses at Recent Venus (IHZ1) and Early Mars (OHZ1) HZs over 100 Myr relative to a 1 per cent $\text{M}_\oplus$ protoatmosphere. Red circles, blue squares, and green triangles represent M4–M10, M0–M4, and FGK stars, respectively.

energy released by flares according to the flare energy ($10^{30}–10^{38}$ erg) and corresponding daily rate ($v_{\text{flare}}$) over 100 Myr can span over several orders of magnitude: for M4–M10 stars, $\sim10^{33}–10^{35}$ erg; for M0–M4 stars, $\sim10^{28}–10^{30}$ erg; and for FGK stars, $\sim10^{37}–10^{39}$ erg (see Fig. 1). If the drop off of $v_{\text{flare}}$ from low to high-energy flares is larger than the difference between their corresponding bolometric energies, then the contribution of these higher-energy flares is minor on long time-scales relative to the more frequent, lower-energy flares. However, in some extreme cases, the high-energy flares were frequent enough to significantly contribute to atmospheric losses.

Next, we show total mass losses over 100 Myr and 1 Gyr time periods with the three-star categories. Mass-loss is expressed in terms of the mass of the planet’s protoatmosphere, which as we described earlier is 1 per cent of the core mass. Fig. 2 shows flare-induced atmospheric loss for planets in IHZ1 (Recent Venus) and OHZ1 (Early Mars), over 100 Myr. It can be seen that six stars (one M4–M10, three M0–M4, two FGK) are able to completely deplete the primordial atmosphere in 100 Myr in IHZ1, and only three stars (one M0–M4, two FGK) in OHZ1. Fig. 3 shows XUV stellar luminosity-induced atmospheric loss over 100 Myr and 1 Gyr in IHZ1, where the former time-scale is before the saturation phase, which is 100 Myr for FGK stars and 600 Myr for M-dwarfs. Although FGK stars induce the most losses over 100 Myr, followed closely by M0–M4, none of them are able to completely deplete the atmosphere. Over 1 Gyr, however, all M0–M4 stars are able to completely deplete the atmosphere. The comparative loss of FGK stars is significantly lower because M0–M4 stars have high irradiation levels in XUV ($L_{\text{XUV}}/L_{\text{bol}}=10^{-3}$) coupled with a longer saturation time.

We now compare atmospheric loss from flares and stellar luminosity. Fig. 4 shows the ratio of flare- to luminosity-induced losses over 1 Gyr in IHZ1 and OHZ1. In both cases, it can be seen that flaring is the dominant source of escape in a significant fraction of M4–M10 stars, and to a lesser degree in other categories over 1 Gyr: $\sim20$ per cent (26/128), $\sim2$ per cent (4/233), and $\sim4$ per cent (5/129) of the M4–M10, M0–M4, and FGK stars, respectively. In Fig. 5, we show the total atmospheric loss from flares and luminosity over 1 Gyr in IHZ1 and OHZ1. While all M0–M4 stars and a small number in the other categories were able to completely erode the primordial atmosphere in IHZ1, a majority of all the stars in OHZ1 were not. We summarize these results in Table 1 where the median mass-loss is given for the three-star categories in six HZs. It can be seen that the median luminosity-induced loss is about an order of magnitude higher than flare-induced loss for M4–M10, and about two orders of magnitude higher for M0–M4 and FGK stars, respectively. Finally,
lower-energy flares tended to dominate as a source of mass-loss in six cases of HZs. We applied the energy-limited escape formula to atmospheric loss from flares and luminosity on different star types factors governing its habitability. We have investigated XUV-induced The ability of a planet to retain its atmosphere is one of the main much earlier as described previously.

Saturation times are much smaller and hence the XUV decline starts FGK stars is considerably lower than that of M-dwarfs because their in Fig. 6, we show the time evolution of the median mass-loss from XUV-induced losses at Recent Venus (IHZ1) over 5 Gyr, where red, blue, and green solid lines represent M4–M10, M0–M4, and FGK stars, respectively.

in Fig. 6, we show the time evolution of the median mass-loss from the three categories of stars over 5 Gyr. The rise in losses from FGK stars is considerably lower than that of M-dwarfs because their saturation times are much smaller and hence the XUV decline starts much earlier as described previously.

4 CONCLUSION AND DISCUSSION
The ability of a planet to retain its atmosphere is one of the main factors governing its habitability. We have investigated XUV-induced atmospheric loss from flares and luminosity on different star types in six cases of HZs. We applied the energy-limited escape formula to calculate hydrodynamic escape. We found that more frequent, lower-energy flares tended to dominate as a source of mass-loss over long time-scales, whereas flares with energies beyond $10^{36}$ erg (superflares) do not make a significant contribution because of their low occurrence rate, except in a limited number of cases (Fig. 1). We only show calculations for total losses induced from these flares over $10^8$–$10^9$ yr. However, if we were concerned with calculating instantaneous losses from an individual flare then we would factor in its duration, $t_{\text{flare}}$, according to its bolometric energy via the following equation (Tilley et al. 2019):

$$t_{\text{flare}} = 10^{0.959 \log_{10}(E_{\text{bol}}) - 9.269},$$

which gives durations of $\sim 4 \times 10^2 - 5 \times 10^5$ s for $E_{\text{bol}} = 10^{30} - 10^{38}$ erg. These flare durations can exceed by more than an order of magnitude that of a recent study for Hot Jupiters (Bisikalo et al. 2018). Indeed, these larger flare durations and the much smaller planetary radii in this study compared to that of the Hot Jupiter study make it difficult to draw direct comparisons.

We have demonstrated that for most stars, luminosity-induced escape is the main loss mechanism, with only a minor contribution from flares. However, flares dominate the loss mechanism of $\sim 20$ per cent M4–M10 stars. M0–M4 stars, because of their high XUV irradiation levels, are able to completely erode the planetary protoatmospheres in all inner HZs, including IHZ3 where the core mass is 5 $M_\oplus$. This contrasts with previous studies (e.g. Erkaev et al. 2016, and references therein) that suggested protoplanetary cores with masses $\geq 5 M_\oplus$ orbiting inside the HZs of M-type stars are likely to keep their hydrogen envelopes. However, when calculating $L_{\text{XUV}}$-induced losses, we assumed escape was always hydrodynamic, which Owen & Mohanty (2016) demonstrated can lead to significant overestimations. If indeed our $L_{\text{XUV}}$-induced losses are overestimations, then our result that flares can induce greater losses is even more significant and likely occurs for more stars. Also, the lack of atmospheric erosion for protoplanetary cores with masses in the range of 0.1–5 $M_\oplus$ orbiting FGK (solar-like) stars within their HZs agrees with Erkaev et al. (2016).

M0–M4 stars are the most likely ones to erode secondary atmospheres, as seen in Fig. 5, because they are able to maintain relatively high XUV irradiation levels over long time-scales. A combination of high XUV from stellar luminosity and flares and small star–planet distance makes these planets especially sensitive to erosion of both proto- and secondary atmospheres. On the other hand, the least likely ones to erode their secondary atmospheres are M4–M10 stars, which consisted of the most stars whose primary loss mechanism was flare-induced. These results have significant implications for planetary habitability because about 75 per cent of stars in the

| Star Type | Flares $(\times 10^{23})$ [g] | $L_{\text{XUV}}$ $(\times 10^{25})$ [g] |
|-----------|-----------------------------|-----------------------------|
| M4–M10    |                             |                             |
| IHZ1      | 7.57                        | 11.2                        |
| OHZ1      | 1.08                        | 1.61                        |
| IHZ2      | 4.72                        | 7.01                        |
| OHZ2      | 1.21                        | 1.79                        |
| IHZ3      | 20.2                        | 30.0                        |
| IHZ4      | 4.08                        | 6.07                        |
| M0–M4     |                             |                             |
| IHZ1      | 7.49                        | 11.3                        |
| OHZ1      | 1.10                        | 1.65                        |
| IHZ2      | 4.67                        | 7.04                        |
| OHZ2      | 1.22                        | 1.84                        |
| IHZ3      | 20.0                        | 30.1                        |
| IHZ4      | 4.04                        | 6.10                        |
| FGK       |                             |                             |
| IHZ1      | 3.28                        | 3.46                        |
| OHZ1      | 0.564                       | 0.597                       |
| IHZ2      | 2.05                        | 2.16                        |
| OHZ2      | 0.628                       | 0.664                       |
| IHZ3      | 8.74                        | 9.22                        |
| IHZ4      | 1.78                        | 1.88                        |
Milky Way are M-dwarfs (Owen & Mohanty 2016) and observations suggest that they host twice the number of planets around them compared to other stars (Hardegree-Ullman et al. 2019). Moreover, the extended atmospheres of these planets are more capable of being observed due to the relatively small ratio of planetary to stellar radius (Lammer et al. 2011). Therefore, based on the substantial losses that can be induced by XUV flares and luminosity at the close-in HZs of the M-type stars, addressing the corresponding expansion of these atmospheres could be useful for observing potentially habitable planets around M dwarfs. However, we did not address this and simply assumed that $R_{\text{XUV}} \sim \rho_\text{p}$ in our energy-limited escape calculations. Also, most planets in OHZ1 ($\sim 99$ per cent) are not significantly impacted by stellar radiation-induced atmospheric loss. This also signifies the importance of planetary composition and structure, which governs the location of the HZ.

There were several caveats in our formulation. The energy-limited equation has been shown to work particularly well for hydrodynamic escape driven by the stellar XUV flux but has been shown to underestimate mass-loss for highly irradiated, low-density planets, where escape is driven by a combination of the planetary intrinsic thermal energy and low gravity; and overestimate mass-loss for planets with hydrostatic atmospheres in which it is controlled by Jeans escape (Kubyshkina et al. 2018, and references therein). Given the large amount of XUV energy from flares deposited into the protoatmospheres of the terrestrial planets at their close proximities to the host star, we expect the ensuing escape to be hydrodynamic. We treat two flares totally independent of each other, which might not be the case for low-energy flares with high occurrence rates. As previously mentioned, we did not apply a more complex absorption/upper atmospheric model to determine $R_{\text{XUV}}$. We applied a constant heating efficiency up to 5 Gyr despite it being shown to vary with time (e.g. Murray-Clay, Chiang & Murray 2009). Moreover, we did not consider any possible radiative cooling that could affect the efficiency (e.g. Owen & Mohanty 2016).

The energy-limited escape formula does not account for neutral losses of an atmosphere, such as dissociation and ionization, as well as subsequent recombination. Erkaev et al. (2016) simulated EUV-driven mass-loss of protoatmospheres and took into account dissociation and ionization of molecular hydrogen and recombination of atomic hydrogen by solving more complex fluid equations for mass, momentum, and energy conservation. They found that energy-limited escape with $R_{\text{XUV}} \sim \rho_\text{p}$ and $R_{\text{XUV}} > \rho_\text{p}$ were lower and upper bounds, respectively, and within an order of magnitude of the sum of atomic and molecular hydrogen escape (see fig. 1 therein). Only about half of the 492 stars (10 M4–M10, 133 M0–M4, and 110 FGK) from the TESS data had information from which we could derive stellar masses. We used these masses to calculate the Roche lobe radii and corresponding stellar tidal effects (Erkaev et al. 2007) and found that $K > 0.95$ for all of the stars. Therefore, due to this relatively small enhancement of escape as well as the fact that only about half the stars had sufficient data to make such a calculation, we neglected this variable when solving the energy-limited escape formula. We use $T_{\text{eff}}$ and $M_{\ast}$ from TESS data to calculate the stars’ current luminosities to determine HZs. However, we do not consider how the luminosity and thus HZs could vary with time nor where in its lifetime these stars may be (e.g. Luger et al. 2015). Our study focuses on erosion or protoatmospheres but we do not consider processes that could protect an atmosphere from being lost to space (e.g. Johnstone et al. 2019). Finally, our study is primarily concerned with the enhanced thermal escape XUV stellar flares can induce; however, we do not consider additional non-thermal escape channels, e.g. charge-exchange interactions between atmospheric neutrals and stellar wind protons.

Atmospheric escape is a complex process and we need a better numerical modelling approach to estimate the total loss by including other channels of escape. We need more flare observations to get a better picture of FFD around a variety of stars. More observations of escaping atmospheres will help in better constraining atmospheric models and aid in understanding the long-term effects of stellar activity on planetary atmospheres and implications on their habitability.

**ACKNOWLEDGEMENTS**

DA acknowledges support from the New York University Abu Dhabi (NYUAD) Institute research grant GI502. SRCM acknowledges support from the NYUAD Global PhD Fellowship.

**DATA AVAILABILITY**

The data underlying this article are available at: https://iopscience.iop.org/1538-3881/159/2/60_suppdata/ajab5d3at1_mrt.txt

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MNARSL 500, L1–L5 (2021)