Transiting Exoplanet Survey Satellite (TESS) Observations of Flares and Quasi-Periodic Pulsations from Low-Mass Stars and Potential Impact on Exoplanets

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Abstract
We have performed a search for flares and quasi-periodic pulsations (QPPs) from low-mass M-dwarf stars using Transient Exoplanet Survey Satellite (TESS) two-minute cadence data. We find seven stars that show evidence of QPPs. Using Fourier and empirical mode decomposition techniques, we confirm the presence of 11 QPPs in these seven stars with a period between 10.2 and 71.9 minutes, including an oscillation with strong drift in the period and a double-mode oscillation. The fraction of flares that showed QPPs (7%) is higher than other studies of stellar flares, but it is very similar to the fraction of solar C-class flares. Based on the stellar parameters taken from the TESS Input Catalog, we determine the lengths and magnetic-field strengths of the flare coronal loops using the period of the QPPs and various assumptions about the origin of the QPPs. We also use a scaling relationship based on flares from the Sun and solar-type stars and the observed energy, plus the duration of the flares, finding that the different approaches predict loop lengths that are consistent to within a factor of about two. We also discuss the flare frequency of the seven stars determining whether this could result in ozone depletion or abiogenesis in any orbiting exoplanet. Three of our stars have a sufficiently high rate of energetic flares, which are likely to cause abiogenesis. However, two of these stars are also in the range where ozone depletion is likely to occur. We speculate on the implications of the flare rates, loop lengths, and QPPs for life on potential exoplanets orbiting in their host star’s habitable zone.

Keywords Stars: activity · Stars: flare · Stars: low-mass · Stars: pulsations · Stars: magnetic fields · Planets and satellites: atmospheres

1. Introduction

The Sun’s variable magnetic activity influences its surrounding heliosphere, which leads to a variety of observed phenomena from small-scale features such as spicules to large-scale events such as flares and coronal mass ejections; the latter of these leads to space weather...
that affects Earth. Flares and coronal mass ejections pose a danger to electric power grids and telecommunications facilities, satellites, and astronauts (e.g. NRC, 2008). Furthermore, the Sun’s radiative output can affect planetary and global climate on much longer timescales from decades to stellar evolutionary timescales (e.g. Mursula, Usoskin, and Maris, 2007, and Nandy et al., 2021). However, we now know that the Sun is much less active than most solar-type stars, although it remains unclear whether the Sun was always less active or whether its activity levels have declined over millions of years (e.g. Reinhold et al., 2020).

Unlike solar-type stars, which have a radiative core and a convective envelope, stars with a mass \( \lesssim 0.4 \, M_\odot \) (corresponding to a \( \approx M4V \) or later spectral type) are fully convective. The fraction of low-mass stars that show optical flares increases from M1V (\( \approx 5\% \)) to M6V (\( \approx 45\% \), Günther et al., 2020), showing that low-mass stars are active. One of the principal factors in determining the degree of flare activity is a star’s age, with activity declining as stars get older (e.g. Skumanich, 1986, and more recently Davenport et al., 2019). Understanding stellar activity in general has become an area of renewed interest for several reasons. Stellar activity can mask or give false positive detections of exoplanets (e.g. Rajpaul et al., 2015), and stellar flares can affect the atmosphere of planets orbiting their host star (e.g. Airapetian et al., 2020). However, in more recent years, it has been argued that the UV flux incident on an exoplanet, which flares can deliver, is essential for life to form (e.g. Rimmer et al., 2018).

In recent years, there have been major advancements in the detection and analysis of quasi-periodic pulsations (QPPs) in solar and stellar flares. These QPPs can appear at all phases of a flare from the impulsive to decay phase. Based on a number of statistical studies, QPPs are shown to be a frequent and wide-spread phenomenon. There are over a dozen possible mechanisms that produce oscillations in a plasma. In flares from M-dwarfs we have seen sub-second pulses in radio bursts (Osten and Bastian, 2006, 2008), a few tens of seconds in ultra-violet data (Doyle et al., 2018), and tens of minutes in optical data from Kepler (Pugh et al., 2016). The proposed models include magnetohydrodynamic waves, repetitive reconnection, and oscillations in current sheets. It is also possible that different mechanisms operate in different flares. By studying these properties we can gain important insights to the physical nature of flares and their immediate environment. This allows for the development of theoretical models that explain the origin and properties of both solar and stellar flares.

The first detection of QPPs in stellar flares was from an M4e-star that showed oscillations in the optical on a period of around a dozen seconds using photoelectric observations (Rodono, 1974). It was much later that QPPs were also seen in X-ray observations of a stellar flare, this time on a period of a dozen minutes (Mitra-Kraev et al., 2005). QPPs with timescales shorter than a dozen minutes have now been seen from many stars; see also Balona et al. (2015). In addition to those given by Pugh et al. (2016), an example of a long-period QPP was from YZ CMi (M4.5e), which had a period of 32 minutes (Anfinogentov et al., 2013). Reale et al. (2018) report X-ray observations of three-hour pulsations in two pre-main sequence stars, implying a very large stellar loop structure. Cho et al. (2016) made a comparison between the observed characteristics of solar and stellar QPPs seen in X-rays and concluded that the underlying mechanism responsible was the same in both the solar and stellar atmospheres. For reviews of QPPs from solar and stellar flares, see McLaughlin et al. (2018), Van Doorsselaere, Kupriyanova, and Yuan (2016), Kupriyanova et al. (2020), and Zimovets et al. (2021).

The means of detecting flares from many stars simultaneously has been transformed with the Kepler and TESS missions. Kepler stared at the same 115 square degree field of view for nearly four years resulting in hundreds of flares being observed from stars of different
spectral types (e.g. Davenport, 2016). TESS has now observed a large fraction of the sky with photometry available for each sector of sky, each lasting approximately a month in duration. Flares have been seen from stars including solar-type stars (e.g. Doyle, Ramsay, and Doyle, 2020; Tu et al., 2020) and M-dwarfs (e.g. Ramsay, Doyle, and Doyle, 2020; Günther et al., 2020). Observations of the nearest star to our Sun, Proxima Centauri (M5.5V), made using TESS, showed two flares with QPPs on a timescale of a few hours (Vida et al., 2019), indicating that TESS could open up a large sample of QPP events from low-mass stars.

In this article, we use TESS data taken with two-minute cadence to search for high-amplitude flares from low-mass stars. We identify those that have relatively long-duration events (a few hours) and show evidence for QPPs in the decline from maximum. We apply a sophisticated set of tests to determine the significance of the candidate QPPs and then determine the length of the flare-loop structures based on the star’s radius and mass. We also discuss the effects of the high-energy flares on the atmosphere of exoplanets and whether QPPs themselves could make an impact. Finally, we draw parallels between stellar and solar activity.

2. TESS Observations

TESS was launched in April 2018 and consists of four 10.5-cm telescopes that observe a $24^\circ \times 96^\circ$ strip (known as a sector) of sky for $\approx 28$ days (see Ricker et al., 2015, for details). Between July 2018 and June 2019, TESS covered most of the southern ecliptic hemisphere (Cycle 1) and between July 2019 and June 2020 covered most of the northern ecliptic hemisphere (Cycle 2). Although there is a band along the ecliptic plane that was not observed, at the ecliptic poles there is a continuous viewing zone where stars can be observed for about one year (to avoid stray light from the Earth and Moon, some areas of the northern hemisphere were not observed as originally intended). Each “full-frame image” has an exposure time of 30 minutes. However, in each sector, photometry with a cadence of two minutes is obtained, with most targets being selected from the community via a call for proposals.

Since our study requires well-sampled light curves with enough resolution to resolve QPPs, we have used two-minute cadence data from Cycles 1 and 2. Using the stars observed in each sector, we have found that 217,834 unique stars were observed in two-minute cadence in Cycles 1 and 2 that were also in Gaia DR2 (Gaia Collaboration et al., 2018). To select low-mass stars, we cross-matched the sky coordinates of our sample with that of Gaia DR2 and obtained the stars $(BP - RP)$ colour. We derived their absolute $G$-magnitude using the parallax and a Galactic scale length $L = 1.35$ kpc (Astraatmadja and Bailer-Jones, 2016). Following Ramsay, Doyle, and Doyle (2020), we chose to select stars that have a Gaia colour $(BP - RP) > 1.8$ and are close to the main sequence. Our selection excludes stars that are likely to be in binary systems, are likely younger than $\approx 30$ Myr, or have significant reddening (which is unlikely for relatively bright nearby M-dwarfs); this gave 15,437 unique stars.

We downloaded the calibrated light curves of our targets from the MAST data archive (archive.stsci.edu/tess/). We initially used the data values for SAP_FLUX, which are the Simple Aperture Photometry values derived using the standard pipeline and normalised each light curve to unity on a sector-by-sector basis. For those stars with data from more than one sector, we made one combined light curve.

For each of the 15,437 light curves, we identified those that had at least one point with a maximum of 1.6 times the mean (corresponding to 0.5 magnitude in amplitude) and was
Stars within 50 pc are shown as small blue dots in the \textit{Gaia} \((BP − RP) − M_G\) plane. Purple dots show those stars that we identified as having candidate QPPs in at least one flare event. Using the work of Pecaut and Mamajek (2013), we find they have a spectral type in the range M3 – M4V.

A total of 481 stars showed at least one flare with an amplitude of 0.5 magnitude and also passed our initial manual verification phase. Of this sample, 178 stars had at least one high-amplitude flare of duration greater than one hour, with 40 having a duration of two hours or more. The light curve of each of the 178 stars was then visually inspected to search for candidate QPPs in the decline from flare maximum. We identified seven stars that show evidence for candidate QPPs events: three stars showed more than one candidate QPP event in separate flares.

The physical and observational characteristics of these stars are outlined in Table 1. We show in Figure 1 the position of these stars in the \textit{Gaia} \((BP − RP) − M_G\) plane. This indicates that they have spectral types around M3 – M4V (www.pas.rochester.edu/emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt), the point where stars become fully convective.

We then considered the issue of the large pixel size (21 arcsec per pixel) of the detectors on the TESS cameras, which can cause variability from spatially nearby stars to contaminate the light curve of the target star. We initially used \texttt{tpfplotter} (Aller et al., 2020) to overlay the position of stars in the \textit{Gaia} DR2 catalogue onto an image derived from a TESS Target Pixel File (see the lower panel of Figure 2). This indicates which, if any, stars were in the aperture mask used to extract the light curve of the target, which typically is 7 – 8 pixels in size. Of the seven stars in our sample, three had no stars within 3 magnitudes of the target in the aperture mask. For the remaining four stars, the stars were 2.8 – 2.9 magnitudes fainter than the target. Using \textit{Gaia} EDR3 data to determine their place on the \textit{Gaia} HRD, we identify the spatially nearby stars as being late-K or early-M spectral types.

The Target Pixel files also allowed us to examine how the position of the centre of the Point Spread Function (PSF) \([\text{MOMCENTR1/2}]\) varied over the observation. It is quite normal for the position of the photocentre to shift by a few 0.01 pixels in \(x, y\) coordinates over the \(\approx 13 – 14\) days that make up half of a sector’s observations. What we find is that even for stars that have no spatially nearby stars in the aperture mask, during more intense flares the photocentre can shift by \(\approx 0.1\) pixels in \(x, y\) coordinates. As an example, we show in the top panel of Figure 2 the position of the centroid of the photocentre of TIC
Table 1 The stellar parameters for the sources for which we have identified QPPs in at least one flare observed using TESS two-minute-cadence data. The data have been extracted from the TIC v8.0 (Stassun et al., 2019) and Gaia DR2.

| TIC ID     | Tmag [2000] | RA [2000] | Dec [2000] | PM_RA [mas yr\(^{-1}\)] | PM_Dec [mas yr\(^{-1}\)] | BP–RP | D [pc] | M\(_G\) | L [erg s\(^{-1}\)] | T\(_{\text{eff}}\) [K] | Radius [R\(_{\odot}\)] | Mass [M\(_{\odot}\)] |
|------------|-------------|-----------|------------|-------------------------|--------------------------|-------|-------|---------|----------------|----------------|-----------------|---------------|
| 1403938    | 13.84       | 140.26158 | -15.89001  | -92.3±0.1               | 30.7±0.1                 | 2.85  | 83.9±0.8 | 10.38   | 5.0×10\(^{31}\) | 3251±157       | 0.371±0.011     | 0.358±0.02    |
| 233547261  | 13.24       | 281.73833 | 60.89595   | 14.8±0.1                | -26.5±0.1                | 2.60  | 78.1±0.4 | 10.02   | 6.4×10\(^{31}\) | 3376±157       | 0.390±0.012     | 0.381±0.02    |
| 279494336  | 12.9        | 59.08738  | -15.80579  | -13.7±0.1               | -46.7±0.1                | 2.62  | 72.9±0.5 | 9.87    | 6.9×10\(^{31}\) | 3366±157       | 0.407±0.012     | 0.399±0.02    |
| 353898013  | 12.63       | 271.89985 | 56.32422   | 22.9±0.1                | 41.2±0.1                 | 2.90  | 43.9±0.2 | 10.75   | 3.8×10\(^{31}\) | 3230±157       | 0.328±0.010     | 0.309±0.02    |
| 455825451  | 12.19       | 322.41897 | 64.09441   | 90.9±0.1                | 28.8±0.1                 | 2.59  | 43.8±0.1 | 10.23   | 5.8×10\(^{31}\) | 3384±157       | 0.369±0.011     | 0.356±0.02    |
| 271698144  | 12.63       | 110.13863 | -75.76763  | -35.8±0.1               | 71.4±0.1                 | 2.51  | 69.6±0.3 | 9.66    | 8.3×10\(^{31}\) | 3429±157       | 0.431±0.013     | 0.426±0.02    |
| 393804343  | 12.93       | 81.32051  | -20.90736  | 20.8±0.1                | -40.7±0.1                | 2.64  | 74.8±0.6 | 9.85    | 7.2×10\(^{31}\) | 3361±157       | 0.418±0.012     | 0.411±0.02    |
Figure 2  Top panel: the light curve of the first flare that we detect in TIC 271698144 colour coded to reflect the detector coordinates in the middle panel. The middle panel shows the centroid of the photocentre of the star, which indicates that during the flare, the photocentre shifts to the upper left. The lower panel shows a map of the immediate field taken from the Target Pixel File with the aperture map shown as red boxes. The spatially nearby stars are all at least five magnitudes fainter than the target. During the flare, the photocentre shifts towards the target. We attribute this to chromatic aberration.

271698144 (one of our selected objects) over the course of a high-amplitude flare: it shifts in $x$, $y$ by a few 1/100 of a pixel towards the target (although in other cases it did not). We also show a map of the immediate field with the location of the aperture mask shown. The spatially nearby stars are at least five magnitudes fainter than the target. The only explanation that we can attribute to this observation is chromatic aberration, which will be sensitive to position of the target in the plane of the detector. During a high-amplitude flare, the colour of the incident light is hotter (bluer), and therefore it could in principle be slightly offset from the previous centroid. This has been studied in depth for Kepler data by Hedges et al. (2021), who show that the shape of the PSF varies depending on the colour and note that due...
Table 2  For those stars showing candidate QPPs: the duration of the TESS light curve, the period taken to be the rotation period, the amplitude of the rotational modulation, the maximum bolometric energy of the flares seen, the total number of flares detected, and the number of flares with QPPs.

| TIC         | Duration [days] | Period [days] | Amp. [frac.] | Max. energy [erg] | Number flares | Number flares with QPPs |
|-------------|-----------------|--------------|-------------|-------------------|---------------|------------------------|
| 1403938     | 18.6            | 0.645        | 0.0104      | $6.0 \times 10^{35}$ | 2             | 2                      |
| 233547261   | 321.6           | 2.450        | 0.0380      | $2.3 \times 10^{36}$ | 24            | 1                      |
| 279494336   | 46.9            | 0.924        | 0.0060      | $6.1 \times 10^{35}$ | 2             | 1                      |
| 353898013   | 321.5           | 1.659        | 0.0294      | $1.1 \times 10^{36}$ | 79            | 1                      |
| 455825451   | 95.5            | 0.478        | 0.0332      | $7.8 \times 10^{35}$ | 31            | 1                      |
| 271698144   | 287.0           | 0.419        | 0.0100      | $8.1 \times 10^{35}$ | 85            | 2                      |
| 393804343   | 45.2            | 0.912        | 0.0202      | $8.7 \times 10^{35}$ | 17            | 3                      |

to the refractive nature of the TESS optics, this effect is likely to be much greater in TESS data. Finally, we note that Jackman, Shkolnik, and Loyd (2021) made a systematic study of flares from M-dwarfs using Kepler and TESS data and concluded that for TESS data there is a 5.8% chance of a false-positive flare event due to spatially nearby stars. We conclude that it is highly unlikely that the flares in which we detect candidate QPPs do not originate from the M-dwarf target.

For each of the seven stars that passed this verification phase, we took the bolometric luminosity of our target stars from the TIC V8.0 catalogue (Stassun et al., 2019). Determining the luminosity of the flares involves some degree of approximation. Unlike the photosphere of the M-dwarf star, the temperature of the flare can be considerably higher. We assume that the temperature of the flare is $\approx 12,000$ K and that the fraction of the emitted flux that falls within the TESS pass-band is $\approx 0.14$ (Schmitt et al., 2019). This implies a correction factor of $\approx 7$ to obtain the bolometric luminosity of the flare (this gives flare energies $\approx 1.5$ greater compared with a temperature of 9000 K (Howard et al., 2019). With this in place, we then removed the signature of the rotational modulation and instrumental effects using a routine in the lightkurve Python package (Lightkurve Collaboration et al., 2018). We then searched for flares and calculated the energy of *all* the flares in that light curve using the Altaipony (altaipony.readthedocs.io/en/latest) suite of Python-based software, which is an update of the Appaloosa (Davenport, 2016) suite of software. To determine the likely rotation period of the stars, we used the light curves derived from the PDCSAP_FLUX values, which are the Simple Aperture Photometry values [SAP_FLUX] after correction for systematic trends and the Lomb–Scargle (LS) Periodogram as implemented in the VARTOOLS suite of tools (Hartman and Bakos, 2016). We show the periods of each star in Table 2, where each period i) was clearly seen in the light curve, ii) has a very low False Alarm Probability, and iii) is within the range 0.4 – 2.5 days. We now go on to a detailed assessment of the candidate QPP events, returning to the wider implications of the rate of high-energy flares from these stars in Section 6.

3. Searching for QPPs

We found seven low-mass M-dwarf stars with candidate QPPs in their TESS light curves. How to detect the presence of QPPs in stellar flares and determine their significance is a challenging task, with many different approaches having been used over the years. Broomhall
et al. (2019) outline the potential pitfalls in these approaches and make a number of recommendations for such searches.

For identifying the flare events to be checked for the presence of QPP patterns in all of the available observations, we begin with assuming $t_{\text{rise}} = 100$ minutes for pre-flare and flare-rising phases and $t_{\text{dec}} = 500$ minutes for the flare decay phase. For each of the light curves, we set a threshold of $3\sigma$, where the standard deviation was derived from the full light curve, and we identify all local maxima exceeding this threshold. From the identified local maxima we select only those where the time interval is greater than 0.3 $t_{\text{dec}}$ (thus we consider the events with multiple maxima situated closer than 0.3 $t_{\text{dec}}$ with respect to each other as a single event). The selected maxima preceded by $t_{\text{rise}}$ and followed by $t_{\text{dec}}$ thus become the list of flaring events for the further QPP analysis (see the red triangles in Figures 3–4 and 9–11).
Figure 4 A two-modal QPP event detected in TIC 271698144. The layout and notations of the top and middle panels are very similar to those shown in Figure 3. The two bottom panels show the individual EMD-revealed modes of this two-modal QPP event.

The analysis of QPP signals that we carried out in this work represents a synergy of the methods used by Broomhall et al. (2019): i) Fourier transform with detrending by smoothing and not taking the background coloured noise into account, ii) a Fourier transform without detrending and accounting for the background coloured noise, and iii) a method of empirical mode decomposition (EMD) with a self-consistent detrending and assessment of the statistical significance of the revealed intrinsic oscillatory modes in comparison with the background coloured noise. More specifically, for each of the identified flare events:

i) We focus on the decay phase of the flare, for the beginning of which we use the time \([t_{\text{peak}}]\) of the flare peak (highest value in the flare light curve) and the above-mentioned \(t_{\text{dec}} = 500\) minutes for its duration.

ii) As a rough estimate of the flare e-folding time \([t_{1/e}]\), we best fit the decay phase of the flare with an exponential function.
iii) To account for the effects of flare trimming on the detection of QPPs (see Section 5.3 in Broomhall et al., 2019), we vary the length of the signal of interest as $[t_{\text{peak}}, t_{\text{peak}} + \tau t_{1/e}]$, where $\tau$ is an integer varying from 2 to 10 in this work.

iv) From the resulting flare sections (i.e. $[t_{\text{peak}}, t_{\text{peak}} + 2t_{1/e}]$, $[t_{\text{peak}}, t_{\text{peak}} + 3t_{1/e}]$, etc.) we select only those in which the number of observational data points is greater than 30. Fewer data points would not allow for a meaningful Fourier or EMD analysis of periodicities.

v) For each of those selected flare sections $F_0(t)$, we subtract the exponential fit $T_{\text{exp}}(t)$ obtained at step ii) as a rough approximation of the flare trend. This gives $F_1(t) = F_0(t) - T_{\text{exp}}(t)$. This allows us to mitigate the discontinuity between the start and end points in $F_0(t)$, which is crucial for the Fourier and EMD techniques.

vi) We apply the EMD method to $F_1(t)$. From all the EMD-revealed intrinsic modes we combine all modes with characteristic time scales longer than 0.4 of the total signal length (so that the number of oscillation cycles in each of those modes is less than 2.5) in a slowly varying trend $T_{\text{EMD}}(t)$ of $F_1(t)$.

vii) We define the total trend of the original flare signal $F_0(t)$ as $T(t) = T_{\text{exp}}(t) + T_{\text{EMD}}(t)$ (see the red solid lines in the top-left panels of Figures 3 – 4), and we subtract $T(t)$ from $F_0(t)$ to obtain the detrended signal $F(t)$.

viii) We apply the Fourier analysis to $F(t)$ (see the top-right panels in Figures 3 – 4) and assess the significance of the Fourier peaks, and obtain parameters of the background noise (i.e. its power-law index, also known as the noise “colour”, and energies of the white and coloured components), adapting the methods from Vaughan (2005) and Pugh, Broomhall, and Nakariakov (2017). We note here that due to the intrinsic non-stationary properties of QPP (i.e. short lifetime, modulation of the oscillation amplitude and/or period), their oscillation energy often gets redistributed across a number of Fourier harmonics, thus lowering the statistical significance of QPP in the Fourier analysis (see, e.g., Nakariakov et al., 2019, for a recent review of this topic). Hence, in this work, we set two significance levels of $1\sigma$ (i.e. 68% confidence) and $2\sigma$ (i.e. 95% confidence) in the Fourier spectra.

ix) From this stage onward, we proceed only with those signals that have the Fourier peaks with significance of at least $1\sigma$.

x) For those signals, we assess the statistical significance of the EMD modes revealed at step vi), following Kolotkov, Anfinogentov, and Nakariakov (2016) and using the parameters of noise obtained from the Fourier analysis at step viii). The corresponding EMD spectra (i.e. the dependence between the EMD-revealed modal energies and mean periods) with the 95% confidence levels are shown in the bottom right panels of Figures 3 – 4.

xi) We consider a QPP event as positively detected in this work if it has at least $1\sigma$ ($68\%$) significance in the Fourier analysis and $2\sigma$ ($95\%$) significance in the EMD analysis.

The application of this scheme allowed us to reveal eleven QPP events (see Figures 3 – 4 and Figures 9, 10, and 11) with mean periods ranging from $10.2 \pm 1.4$ minutes to $71.9 \pm 13.0$ minutes (see Table 3), including one QPP signal with a strong drift in the oscillation period (see Figure 3) and one two-modal QPP signal (see Figure 4). In the QPP event shown in Figure 3, the instantaneous oscillation period is clearly seen to decrease with time from about 40 minutes to 20 minutes, unless the QPP oscillation amplitude becomes comparable to the amplitude fluctuations caused by noise. Because of such strong non-stationarity, the Fourier power of this oscillation is seen to be spread between 20 minutes and 40 minutes, which resulted in overall lowering the height of the corresponding Fourier peak below the 95% significance level. In contrast, in the EMD method the basis for decomposition is not...
Table 3 For those stars showing QPPs: the flare energy; the QPP period; the duration of the flare based on the flux returning close to the pre-flare flux; the duration of the flare based on the e-folding time; the loop length assuming the QPP-driving mechanism is due to compressive standing slow magneto-acoustic oscillations \(l_{\text{slow}}\); the loop length via long-wavelength kink oscillations \(l_{\text{kink}}\); the loop length based on the predictions of the coronal magnetic-field strength and loop length from Namekata et al. (2017) \(l_N\); the loop length compared to the star’s radius; the estimated magnetic field of the starspot \(B_{\text{spot}}\) and the coronal magnetic field \(B_{\text{cor}}\). For the first QPP event in TIC 271698144, the loop lengths are derived for the longer period QPP.

| TIC          | Energy flare [erg] | Period QPP [min] | Dur. [min] | e-fold [min] | \(l_{\text{slow}}\) [Mm] | \(l_{\text{kink}}\) [Mm] | \(l_N\) [Mm] | \(l_{\text{slow}}/R^*\) | \(B_{\text{spot}}\) [kG] | \(B_{\text{cor}}\) [G] |
|--------------|---------------------|------------------|------------|--------------|--------------------------|--------------------------|----------------|--------------------------|--------------------------|--------------------------|
| 1403938      | \(6.0 \times 10^{35}\) | 21.5             | 85         | 21.2         | 440                      | 640                      | 580           | 1.69                     | 2.5                      | 250                      |
| 1403938      | \(1.0 \times 10^{34}\) | 36.6             | 145        | 16.1         | 750                      | 1000                     | 160           | 2.87                     | 2.5                      | 230                      |
| 233547261    | \(7.5 \times 10^{35}\) | 25.8             | 200        | 25.2         | 530                      | 740                      | 730           | 1.93                     | 2.0                      | 240                      |
| 279494336    | \(6.1 \times 10^{35}\) | 39.8             | 120        | 31.3         | 810                      | 950                      | 760           | 2.85                     | 4.0                      | 200                      |
| 353898013    | \(8.2 \times 10^{34}\) | 19.8             | 78         | 20.2         | 400                      | 400                      | 330           | 1.76                     | 1.6                      | 170                      |
| 455825451    | \(1.1 \times 10^{34}\) | 71.9             | 289        | 11.9         | 1470                     | 1380                     | 230           | 5.68                     | 1.4                      | 160                      |
| 271698144    | \(3.4 \times 10^{35}\) | 25.4/62.9        | 250        | 19.5         | 1810                     | 1660                     | 570           | 1.74                     | 3.2                      | 240                      |
| 271698144    | \(4.0 \times 10^{34}\) | 10.2             | 60         | 39.0         | 210                      | 120                      | 490           | 0.69                     | 3.2                      | 100                      |
| 393804343    | \(1.6 \times 10^{34}\) | 13.6             | 78         | 16.6         | 280                      | 230                      | 280           | 0.95                     | 2.0                      | 140                      |
| 393804343    | \(4.3 \times 10^{35}\) | 19.7             | 116        | 19.8         | 400                      | 580                      | 600           | 1.37                     | 2.0                      | 245                      |
| 393804343    | \(1.3 \times 10^{34}\) | 18.5             | 140        | 32.1         | 380                      | 200                      | 350           | 1.29                     | 2.0                      | 90                       |

prescribed a priori but is derived directly from the data by iterative sifting its local time scales (Huang et al., 1998). This makes the EMD method more suitable for capturing the non-stationary oscillatory processes in general and QPP in solar and stellar flares with strong period drifts in particular; see, e.g., Section 5.4 in Broomhall et al. (2019), Sections 3.3 and 4.4 of Kupriyanova et al. (2020), and references therein.

In the example shown in Figure 3, the application of EMD allowed the retaining of the energy of a non-stationary oscillatory process seen in the detrended observational signal in a single intrinsic mode (i.e. not distributed over a number of modes or harmonics), which resulted in the statistical significance of this mode above 95% in the EMD spectrum. In the two-modal QPP event (Figure 4), both modes are seen to have rather stable periods with mean values of 25.4 ± 6.6 minutes and 62.9 ± 7.8 minutes, and the statistical significance about or higher than 95% in both the Fourier and EMD approaches. Although the periods of these two modes are longer than a multi-mode flare seen in a pre-main-sequence M3-star identified in NGTS data (Jackman et al., 2019), the ratio of the short to long periods are consistent to within about a factor of two.

By making certain assumptions concerning the nature of the physical mechanism producing the flares, various studies, including those of Mathioudakis et al. (2006) and Jackman et al. (2019), were able to estimate the loop length of the flares where the QPPs originate. To do this, we must first estimate the strength of the magnetic field in the M-dwarfs.

4. Magnetic-Field Strengths

Determining the magnetic-field strength (or upper limit) of any star can be achieved, in principal, using spectropolarimetric data, but this requires considerable telescope time and
is restricted to relatively bright stars; e.g. Reiners (2012). However, there are other indirect means to estimate the magnetic-field strength of a star, provided that it shows evidence of rotational modulation. To estimate the magnetic-field strength of the stars showing QPPs, we begin by using the formula of Maehara et al. (2012) and Notsu et al. (2019) to determine the area of spot coverage:

\[
\frac{\Delta F_{\text{rot}}}{F} \sim \left[1 - \left(\frac{T_{\text{spot}}}{T_{\text{star}}}\right)^4\right] \frac{A_{\text{spot}}}{A_{\text{star}}},
\]

(1)

where \(\Delta F_{\text{rot}}/F\) is the amplitude of the rotational modulation, \(T_{\text{spot}}\) and \(T_{\text{star}}\) are the spot and stellar effective temperature, respectively, \(A_{\text{spot}}\) is the area of the star covered by the spot(s), and \(A_{\text{star}}\) is the area of the star. To determine the difference between the starspot and the mean photospheric temperature, we use the formula of Notsu et al. (2019)

\[
T_{\text{star}} - T_{\text{spot}} = 3.58 \times 10^{-5} T_{\text{star}}^2 + 0.249 \quad 808,
\]

(2)

where we take the effective temperature of the star \(T_{\text{star}}\) from the TIC v8.0 catalogue (Stassun et al., 2019). The magnetic-field strength can then be estimated using the relationship derived by Shibata et al. (2013):

\[
E_{\text{flare max}} = 7 \times 10^{32} \text{ erg} \left(\frac{f}{0.1}\right) \left(\frac{B}{10^{3}}\right)^2 \left(\frac{A_{\text{spot}}/2\pi R^2}{0.001}\right)^{3/2},
\]

(3)

where \(E_{\text{flare max}}\) is the maximum bolometric energy of the flare we detect in that star’s light-curve, \(f\) is the fraction of the magnetic energy that can be released as flare energy (which we fix at 0.1 as done by Shibata et al. (2013)), and \(A_{\text{spot}}\) is the area of the spot (taken from Equation 1).

Using the equations above, we can determine the relationship between the relative size of the starspot and the maximum energy of the flare, which we show in Figure 5. Using Equation 3, we can derive the magnetic field of the starspot as a function of area and energy and find \(B \approx 1 - 4\) kG. These field strengths are consistent with the magnetic field of starspots in M dwarf stars; e.g. Morin et al. (2008).
5. Loop Lengths

Roberts, Edwin, and Benz (1984) outlined how the QPPs seen in solar flares could be used to determine the loop length of solar coronal loops and the physical conditions in their immediate environment. The same principles have been used to determine properties of stellar flares using observations of QPPs. Mathioudakis et al. (2006) approximate the formula for the period and loop length as

\[
\text{Period[sec]} = \frac{l_{\text{slow}} [\text{Mm}]}{7.6 \times 10^{-2} N \sqrt{T}[\text{MK}]}.
\]

where \(l_{\text{slow}}\) is the loop length in Mm, \(N\) is the node of oscillation (\(N = 1\) for the fundamental, \(N = 2\) for the first harmonic), and \(T\) is the average temperature of the corona along the flare loop, which Mathioudakis et al. (2006) take to be 20 MK. The above equation assumes that the QPP-driving mechanism is due to compressive, standing, slow magneto-acoustic oscillations in coronal loops, where the oscillation period is prescribed by the loop length and the sound speed (i.e. square root of temperature).

Assuming that \(N = 1\), we show the derived loop lengths in Table 3, which are in the range \(\approx 200 – 1800\) Mm (they are twice these values if \(N = 2\)). Taking the radius of each star from the TIC (Stassun et al., 2019), we find that the loop lengths are typically of the same extent (or greater) as the stellar radius. This is consistent with a study of 44 stars with F–M spectral type, which showed that the loops with the largest length to stellar radius ratio (\(\approx 2R_{\star}\)) originated on M-dwarfs (Mullan et al., 2006) with the length of the shortest loops being comparable to that estimated for the flare reported by Jackman et al. (2019).

An alternative way of deriving the loop length is via the scaling laws used by Namekata et al. (2017). Taking the flare duration and energy of those flares as outlined in Table 3, we place them in context by adding them to Figure 9 of Namekata et al. (2017), which shows the energy and duration of solar flares and solar-like stars. Our sample of low-mass stars is comparable with the more energetic flares from solar-like stars. We can estimate the loop lengths of the flares in our sample by comparing their location in Figure 6 with the theoretical relationships for coronal magnetic strength and loop length taken from Namekata et al. (2017). Given the uncertainties in the assumptions, the resulting loop lengths are similar to those estimated assuming that they are driven by slow magneto-acoustic oscillations. However, no matter which wave mode we use, these loop lengths estimates clearly imply very large active regions covering a significant factor of the stellar surface.

However, alternative QPP-driving options are possible, e.g. fast magneto-acoustic waves, which include the kink oscillations of coronal loops situated in, or nearby, the flaring active region (Nakariakov et al., 2006). The period of standing kink oscillations is prescribed by the loop length and the Alfvén speed inside the loop (Nakariakov and Kolotkov, 2020). Here we have two unknowns, the loop length and the Alfvén speed. In Section 4, we estimated a photospheric magnetic field typically in the range \(\approx 1 – 4\) kG. There are obvious uncertainties in predicting the coronal magnetic-field strength (the uncertainty in the height of the loop above the photosphere and the magnetic-field configuration), but a reduction of a factor of ten is reasonable. This yields coronal magnetic-field strengths roughly \(\approx 100 – 300\) G (see Table 3), which are in excellent agreement with those derived from Figure 6. We can use the equation

\[
\text{Period} = \sqrt{2}l_{\text{kink}}/C_{\text{Alfvén}},
\]

where \(l_{\text{kink}}\) is the loop length, and \(C_{\text{Alfvén}}\) is the Alfvén speed based on the derived magnetic-field strength, assuming the fundamental (global) harmonic (see Equation 9 of Nakariakov
Figure 6  A comparison of the bolometric energy and duration of solar and stellar flares, which is inspired from Figure 9 of Namekata et al. (2017), which incorporates work from Maehara et al. (2015). Solar data are shown as orange dots whilst blue dots show super-flares from solar-type stars using Kepler data with one-minute cadence. The large red dots are the sources shown in this article, where the energies and duration are derived from TESS data. We can use the relationships derived for different magnetic-field strength and loop length to estimate these quantities for the stars presented in this article.

and Kolotkov (2020)) and a density $\rho_o = 1 \times 10^{-9} \text{ kg m}^{-3}$, which implies the electron number density $N_e \approx 1 \times 10^{12} \text{ cm}^{-3}$ Monsignori Fossi et al. (1996) found that in the corona of active M-dwarfs, $N_e > 1 \times 10^{12} \text{ cm}^{-3}$ during activity and $N_e \approx 1.5 \times 10^{13} \text{ cm}^{-3}$ during flares. The derived loop lengths (Table 3) are in good agreement with the lengths derived via the compressive-standing-slow mode. The sound speed $C_s$ is about the same as the Alfvén speed $C_{\text{Alfvén}}$, i.e. the plasma parameter $\beta = 2C_s^2/(\gamma C_{\text{Alfvén}}^2)$ is around unity. In solar flares, such high values of $\beta$ have been observed; e.g. high-energy X-class flares require high temperatures and both the plasma-$\beta$ and volume filling factor cannot be much less than unity in the super-hot region; see Caspi, Krucker, and Lin (2014).

We now comment briefly on the parameters for flare energy, duration, loop lengths, and magnetic field reported in Table 3. Given that the loop lengths are directly linked to the period of the QPP (Equation 4), there is a clear correlation between these parameters and also period and duration: long-duration flares can have long-period QPPs, whilst short-duration flares cannot. Similarly, the correlation between magnetic-field strength and duration of the flare comes from the scaling relations of Namekata et al. (2017). Perhaps surprisingly, we find no correlation between the flare energy and flare duration.

6. Flare Rates and the Effects on Potential Exoplanets

We now return to the overall flare rates of the seven stars for which we have identified QPPs. We show these rates in Figure 7 as a cumulative flare frequency distribution (FFD). The seven stars show flares with bolometric energies $> 10^{35} \text{ erg}$ occurring at a rate of 1 per $\approx 10 – 100 \text{ days}$; these are higher rates than the average rates for M3V – M4V stars (Howard et al., 2019).

We do not examine the physical mechanism that enables these stars to produce high-energy flares at such high rates. Rather, we examine what effect these flares may have on
The flare frequency distribution (FFD) for flares of given energy for all seven stars in our sample that show QPPs. The solar FFD, during both maximum and minimum, has maximum energies that are lower than the minimum energy shown here. We show the regions where terrestrial exoplanets in the habitable zone will have ozone in their atmosphere depleted and also lie in the abiogenesis zone, which were taken from Figure 11 of Günther et al. (2020), which was adapted from Tilley et al. (2019) and Rimmer et al. (2018). The atmosphere of any orbiting exoplanet. Over the past 25 years, nearly 4300 exoplanets have been discovered with thousands more awaiting confirmation. As a result, we now know that the majority of main-sequence stars are likely to host planetary systems. Furthermore, the study of stellar activity (including flares) on these host stars has become particularly prominent in exoplanet research. This is due to the impact on the exoplanet atmosphere and the existence of life along with the potential of exoplanet signals being masked by stellar variability.

It is widely known that for life to exist, the planet must lie within the habitable zone (HZ) of the star. This is a planet’s distance from the star where liquid water is likely to pool on the surface. However, this is not the only requirement for life. Rimmer et al. (2018) use experimental chemistry along with stellar physics to determine how much energy would be needed for abiogenesis (natural process where life arises from non-living matter) to occur. They compute this for a sample of low-mass stars from Davenport (2016), concluding that ≈20% of early M-dwarfs are active enough for any host planets to be in the abiogenesis zone. The abiogenesis zone indicates where the stellar UV flux is large enough to result in a 50% increase of the photo-chemical product (i.e. those products that are present in the nucleotide synthesis pathway; see Figure 1 of Rimmer et al. (2018) for more details).

Furthermore, there is an ozone-depletion region where flare rates can cause ozone loss for a planet orbiting in the HZ around an M-dwarf. Understanding the effects of flaring activity on an exoplanet atmosphere is essential in predicting whether there may be life on the surface of the planet. The exoplanet could well be in the HZ; however, it may also be bombarded by electromagnetic and particle radiation from the star. Tilley et al. (2019) looked into this in more detail using models to investigate the effects of repeated flaring on the photochemistry and surface UV of an Earth-like planet (unprotected by a magnetic field) orbiting an M-dwarf. Overall, they found coronal mass ejections (CMEs), which are commonly associated with flares possessing energies > $10^{34}$ erg, were the primary factor in ozone depletion at a rate greater than once every ten days. The ozone is particularly important for the existence of surface life, as this thin layer is responsible for absorbing almost all of the harmful UV radiation.

We have taken the location of the ozone depletion and abiogenesis zones from Figure 11 of Günther et al. (2020), who have determined the abiogenesis zones for FGKM stars and for flare energies in the $U$ and the bolometric energies (as we have derived). Specifically, we use the regions determined for M0–M4 stars. As can be seen from Figure 7, three stars have...
FFDs that overlap with the ozone-depletion zone. This means that any potential exoplanets orbiting these stars could have their ozone layer destroyed by the constant flaring activity. The frequency of this high-energy flaring means that the atmosphere of an exoplanet is unlikely to have time to recover, being destroyed over a prolonged period of time assuming the absence of a magnetic-field environment. However, whether a magnetic field adds sufficient protection remains unanswered. For example, the magnetised Earth has a relatively thick atmosphere, whereas Mars, which is unmagnetised, does not. However, on the other hand, Venus, which is also unmagnetised, has a relatively thick and dense atmosphere. Regardless of this, the UV radiation exposure at the surface of potential exoplanets would make it difficult for surface life to exist. This does not rule out the existence of life altogether, as there could be some present below the ocean surfaces.

There are three stars in the sample that have FFDs that extend to the abiogenesis zone: TIC 393804343, TIC 1403938, and TIC 279494336. For these stars, this is significant as it indicates that the high-energy flares of $\approx 5 \times 10^{35}$ erg at a frequency of one every $\approx 20–50$ days are an important factor in the potential for life on any orbiting exoplanets. However, there is a delicate balance where too many high-energy flares at a high frequency can cause ozone depletion. We see an example of this in TIC 1403928 and TIC 393804343, which lie in both the ozone and abogenesis zones. The question for these particular stars is whether any orbiting planet’s atmosphere will have enough time to recover, allowing for abiogenesis and surface life potentially to exist. The remaining stars do not lie in either the abiogenesis or ozone-depletion zones, although they do show high-energy flares but at rates slightly lower than required to be in the abiogenesis zone. As a result, the ozone layer on any orbiting planets will likely remain intact, and the UV flux is not high enough to sustain prebiotic chemistry. This does not mean that there is no potential for any surface life on orbiting planets, just that it is less likely to manifest without the natural environment needed.

Most M-dwarfs have not been observed in the EUV/UV. However, Melbourne et al. (2020) derived a relationship between CaII H and K and Hα with various strong FUV/NUV lines. The derived scaling relations may be sufficient for photochemical modelling needs, but not atmospheric escape modelling, although an accurate estimate of the Lyα flux should account for $\approx 75\%$ of the FUV in the quiescent state and $\approx 50\%$ during a flare (Diamond-Lowe et al., 2021). Unfortunately, we do not yet have the CaII Ha n dKo rHα flux for these objects.

In Figure 8, we show a schematic plot of how far the coronal loops extend out from the stellar surface in relation to the HZ. In determining this, we assume that the loops are semi-circular arcs that are equal to the loop length. As a result, the radius of the arc is then the distance at which the loop extends out from the stellar surface and can be calculated as $R_{\text{loop}} = l/\pi$. It is important to note that this yields a conservative estimate on the radius of the loop, as most loops are not perfect semi-circular arcs but appear more elliptical in shape. However, for the purposes of this article, assuming a semi-circular arc is acceptable. For stars that possessed more than one QPP event, in Table 3 the QPP with the largest loop length was used. The HZ boundaries were calculated using Kopparapu et al. (2013, 2014) taking the effective stellar temperature $T_{\text{eff}}$ and luminosity $L$ from Table 1.

It is important to note that none of the targets in this sample have any known exoplanets according to the NASA Exoplanet Archive (exoplanetarchive.ipac.caltech.edu/). This does not mean that there are none present at all, just that none have been detected around these stars as of yet. In fact, the occurrence rate for exoplanets orbiting mid-M-dwarfs is on average 1.2 planets per star (Hardegree-Ullman et al., 2019) so, each of these targets is expected to have at least one orbiting exoplanet.
Figure 8  A schematic diagram showing how far the coronal loops (compressive standing slow mode) extend out from the stellar surface, relative to where the HZ lies from the star. The inner HZ boundary is shown for 0.1 (dotted), 1 (dashed), and 5M$_{\oplus}$ (dash–dot), and the outer boundary lies between 0.2 and 0.3 AU (not shown in the diagram). These HZ boundaries were calculated using Kopparapu et al. (2013, 2014), and loop lengths $l_{\text{slow}}$ were taken from Table 3.

7. Discussion

The promise of finding QPPs in TESS observations of low-mass dwarf stars was demonstrated in observations of Proxima Centauri, which showed oscillations on a period of several hours in the decay phase of two flares (Vida et al., 2019). The work presented here shows the scope for identifying and analysing QPPs from a larger sample of low-mass stars using TESS data.

Of the 178 M-dwarfs that we detected at least one flare with an amplitude corresponding to $>0.5$ magnitude and duration longer than one hour, we found 11 flares from 7 stars that showed QPPs. Therefore only 4% of the stars showed flares with QPPs.

However, of those stars that did show QPPs, we find a very diverse rate for the fraction of flares that showed QPPs. For instance, QPPs were detected in both of the two flares seen in TIC 1403938. In contrast, for TIC 353898013 only one out of 79 flares showed a QPP. However, those stars with relatively high fractional rates also have the shortest duration of observations, so this may simply be an observational bias.

In several instances the flare showing QPPs was not the most energetic event of that star, which raises a question of the excitation of waves in stellar atmospheres by powerful flares, to be addressed in follow-up work. However, we note that the 11 QPP events detected in this work constitute 7% of the total number of flares examined (150), which is a factor of two greater than the statistics of stellar QPPs previously reported (Balona et al., 2015; Pugh et al., 2016), and this fraction coincides with the fraction of solar C-class flares that show QPPs (Hayes et al., 2020). We now briefly discuss the robustness of the loop lengths that we derive and the effect of QPPs on any orbiting exoplanets, and we look ahead to future observations.

7.1. Loop Lengths and Scaling Laws

As outlined in Section 1, there are over a dozen possible QPP mechanisms. However, since we are dealing with oscillations with periods of tens of minutes, most of these are not possible. In each of the QPP mechanisms discussed in Section 5, we have made a number of
assumptions. For example, with the slow-mode waves, we assume a coronal flare temperature of 20 MK; using, say, 10 MK instead will decrease the estimate by \( \approx 30\% \) (\( \propto \sqrt{T} \)). For the kink waves, there is some uncertainty regarding the plasma density. In flare conditions the density can be high; e.g. an order of magnitude increase will decrease the Alfvén velocity and the loop length by a factor of three. Considering the various approximations and assumptions used in all three loop-length calculations, the derived lengths can only be considered good to an accuracy of a factor of two. Nevertheless, the derived lengths are all comparable with the star’s radius and, as shown in the illustration in Figure 8, these loops extend high into the star’s corona, thus providing intense UV radiation into a planet’s HZ.

Whilst we considered the kink and slow magneto-acoustic modes of a coronal loop as the most common and straightforward mechanisms for QPPs, a more detailed discussion of this question is beyond the scope of this work. Indeed, the problem of the association of the observed QPP signals with the wave and oscillatory phenomena in solar and stellar atmospheres has been actively debated for at least the last fifteen years and still remains an open question (Zimovets et al., 2021). To address the question of which mechanism drives the QPP events and to gain a better understanding of the physical mechanism producing white-light flares will require many more QPPs to be detected and studied.

### 7.2. Possible Effects of QPPs on Orbiting Exoplanets

Since the launch of TESS, the discovery of planets orbiting M-dwarf host stars has rapidly increased. These low-mass stars spend billions of years on the main sequence due to their cooler temperature. As a result, this would provide enough time for life to flourish on the surface of orbiting exoplanets, making the study of exoplanet habitability of particular importance. In Section 6, we discussed the flare energy and rate of our M-dwarf sample and whether any of the stars possess the conditions needed for abiogenesis or ozone depletion. However, we did not discuss the effects of QPPs on the atmosphere of an exoplanet. Hayes et al. (2017) investigated the effects of solar flare X-ray QPPs on the Earth’s atmosphere. They found that pulsations within the lower ionosphere of the Earth matched those of observed solar QPPs. This QPP-driven periodic modulation of the conditions in Earth’s lower ionospheric (e.g. the electron number density) could result in phenomena such as acoustic gravity waves (e.g. Nina and Čadež (2013)), and disruptions in high-frequency radio-wave propagation (e.g. Frissell et al. (2019)), implying that a similar response could be found in exoplanet atmospheres.

If a planet were orbiting close enough to the host star, then magnetospheric interactions could be possible. This is when the host star and close-in planet’s magnetic fields interact causing star–planet interactions (SPIs) in the form of increased chromospheric emission and possibly flaring (see Ip, Kopp, and Hu (2004), Cohen et al. (2010), and Strugarek et al. (2014). In our stars, we have coronal loops that extend out to between 0.008 to 0.03 AU (see Figure 8). None of the stars in our sample has known exoplanets; however, there have been exoplanets detected around other low-mass stars within this range (e.g. the TRAPPIST-1 system Gillon et al., 2017). TRAPPIST-1 has seven planets orbiting an M8-dwarf star with semi-major axis between 0.01 and 0.06 AU. This means that at least four of the planets are orbiting the star within the range of the coronal loops we observe on our sample. Therefore it is possible to have planets orbiting within the loops outside the HZ, causing SPIs with the host star. The effects this would have on the planet would make it unlikely for any surface life to exist due to an increase in flare activity resulting in an onslaught of harmful radiation.
8. Future Observations and Conclusions

The TESS spacecraft completed its primary mission (covering Cycle 1 and 2) in July 2020, during which it covered the majority of the sky. In each hemisphere, there was an area at each ecliptic pole known as the continuous viewing zone where stars could be observed for a year (some gaps are present due to roughly monthly field repointing). During Cycles 1 and 2, around 20,000 stars were observed in two-minute cadence mode with 30-minute cadence data being available for all stars through full-frame image data.

The extended mission started in July 2020 by reobserving the southern ecliptic hemisphere. There was, however, a clear difference in the cadence of targets. Around 600 targets will be made available to be observed in 20-second cadence through the Guest Observer Programme, and 15,000 targets will be observable in two-minute cadence mode. The full-frame images will now be made available with a cadence of ten minutes.

Bright low-mass dwarfs, which have already been shown to be flare active, will be excellent targets to observe in 20-second cadence mode as it will provide increased time resolution of QPP events. This is especially true for shorter-period QPPs, which will possess shorter loop lengths. For long-duration flares, the full-frame data will prove useful in extending the sample of stars showing QPP events.

Stars that have shown QPPs in TESS data will be excellent targets to be observed using high-cadence ground-based imagers such as ULTRACAM. Previous observations made using ULTRACAM have allowed the colour, and hence temperature, of the flare to be determined over the event, which have provided the base material to test competing models, which give rise to the QPP events (e.g. Kowalski et al., 2016). The derived loop sizes from the QPPs are consistent with work by Cohen et al. (2017), who found that at high latitudes the corona and its X-ray emission are dominated by star-size large hot loops. These authors suggested that in rapidly rotating stars, emission from such coronal structures dominates the quiescent saturated X-ray emission.

The work presented here shows the scope for identifying and analysing QPPs from a larger sample of low-mass stars. We found seven stars that show a total of 11 QPP events, one of which is a double-mode event. With future TESS 20-second cadence data, we can expand on this work sampling shorter periods which will allow a better comparison with solar data. For example, Hayes et al. (2020) analysed 5519 solar flares observed in the X-ray, covering X-, M-, and C-class events in the past solar cycle. Looking at periodicities in the 6 – 300 second timescale, the authors found QPPs in 46% of X-class, 29% of M-class, and 7% of C-class flares. The data used here do not allow us to search this period range, but future TESS data will allow us to look for periods down to ≈ 60 seconds and in particular look at events with energy classifications ranging up to X100,000, an energy range not possible for solar flares.

Using the observed properties of the stars, we estimate the length of the loops giving rise to the flares: they are typically of the order of the stellar radius. The observed properties of QPPs are found to be consistent with the interpretation in terms of magneto-acoustic waves potentially present in the atmospheres of the observed stars. However, we could not discriminate between the fast or slow magneto-acoustic modes because they have rather similar observational properties in high-β flaring plasmas. We fully expect other QPPs to be identified in future TESS data.

Appendix: QPP Signals

In Figure 3, we showed the details for identifying the QPP signal in TIC 233547261, and in Figure 4 in TIC 271698144. Here we show similar figures for the remaining QPPs.
Figure 9 The QPP signals detected in observations of TIC 1403938 and TIC 271698144. Top-left: the flare light curve (the black line) and a low-frequency trend $T(t)$ of its decay phase (the red line), obtained as described in Section 3, step vii). The vertical-dashed lines indicate the time interval of interest. The red triangle shows the position of the apparent flare peak (the highest value in the light curve). Bottom-left: The original flare section of interest with the low-frequency trend subtracted (the black line). The blue line shows the EMD revealed statistically significant intrinsic mode. Top-right: the Fourier power spectrum of the detrended flare signal shown in the bottom-left panel in black. The blue solid line shows the best-fit of the spectrum by a power-law function representing a superposition of the white and coloured noise. The green and red solid lines indicate the statistical significance levels of 1 $\sigma$ (68%) and 2 $\sigma$ (95%), estimated as described in Section 3, step viii). The vertical-blue-dashed line indicates the oscillation period equal to 0.4 of the total analysed signal length. All the EMD-revealed intrinsic modes with mean periods longer than what could be attributed to the low-frequency trend $T(t)$ in this work. Bottom-right: The EMD spectrum (dependence between the EMD-revealed modal energies and mean periods) of the original flare section of interest with the exponential trend $T_{\text{exp}}(t)$ subtracted; see steps v) and vi) in Section 3. The blue solid line shows the expected behaviour of a power-law distributed noise with parameters estimated from the Fourier analysis. The red solid lines show the confidence levels of 95% estimated as described in Section 3, step x). The error bars for the values of the EMD-revealed mean modal periods are estimated as the half-level-width of the global wavelet spectra calculated for each of the intrinsic modes and best-fitted by the Gaussian function.
Figure 10  The QPP signals detected in observations TIC 279494336, TIC 353898013, and TIC 455825451. 
Top-left: the flare light curve (the black line) and a low-frequency trend $T(t)$ of its decay phase (the red line), obtained as described in Section 3, step vii). The vertical-dashed lines indicate the time interval of interest. The red triangle shows the position of the apparent flare peak (the highest value in the light curve). Bottom-left: The original flare section of interest with the low-frequency trend subtracted (the black line). The blue line shows the EMD revealed statistically significant intrinsic mode. Top-right: the Fourier power spectrum of the detrended flare signal shown in the bottom-left panel in black. The blue solid line shows the best-fit of the spectrum by a power-law function representing a superposition of the white and coloured noise. The green and red solid lines indicate the statistical significance levels of $1\sigma$ ($68\%$) and $2\sigma$ ($95\%$), estimated as described in Section 3, step viii). The vertical-blue-dashed line indicates the oscillation period equal to 0.4 of the total analysed signal length. All the EMD-revealed intrinsic modes with mean periods longer than what could be attributed to the low-frequency trend $T(t)$ in this work. Bottom-right: The EMD spectrum (dependence between the EMD-revealed modal energies and mean periods) of the original flare section of interest with the exponential trend $T_{exp}(t)$ subtracted, see steps v) and vi) in Section 3. The blue solid line shows the expected behaviour of a power-law distributed noise with parameters estimated from the Fourier analysis. The red solid lines show the confidence levels of 95% estimated as described in Section 3, step x). The error bars for the values of the EMD-revealed mean modal periods are estimated as the half-level-width of the global wavelet spectra calculated for each of the intrinsic modes and best-fitted by the Gaussian function.
Figure 11 The QPP signals detected in observation TIC 393804343. Top-left: the flare light curve (the black line) and a low-frequency trend $T(t)$ of its decay phase (the red line), obtained as described in Section 3, step vii). The vertical-dashed lines indicate the time interval of interest. The red triangle shows the position of the apparent flare peak (the highest value in the light curve). Bottom-left: The original flare section of interest with the low-frequency trend subtracted (the black line). The blue line shows the EMD revealed statistically significant intrinsic mode. Top-right: the Fourier power spectrum of the detrended flare signal shown in the bottom-left panel in black. The blue solid line shows the best-fit of the spectrum by a power-law function representing a superposition of the white and coloured noise. The green and red solid lines indicate the statistical significance levels of 1 $\sigma$ (68%) and 2 $\sigma$ (95%), estimated as described in Section 3, step viii). The vertical-blue-dashed line indicates the oscillation period equal to 0.4 of the total analysed signal length. All the EMD-revealed intrinsic modes with mean periods longer than what could be attributed to the low-frequency trend $T(t)$ in this work. Bottom-right: The EMD spectrum (dependence between the EMD-revealed modal energies and mean periods) of the original flare section of interest with the exponential trend $T_{\text{exp}}(t)$ subtracted; see steps v) and vi) in Section 3. The blue solid line shows the expected behaviour of a power-law distributed noise with parameters estimated from the Fourier analysis. The red solid lines show the confidence levels of 95% estimated as described in Section 3, step x). The error bars for the values of the EMD-revealed mean modal periods are estimated as the half-level-width of the global wavelet spectra calculated for each of the intrinsic modes and best-fitted by the Gaussian function.
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Declarations

Disclosure of Potential Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

Airapetian, V.S., Barnes, R., Cohen, O., Collinson, G.A., Danchi, W.C., Dong, C.F., Del Genio, A.D., France, K., Garcia-Sage, K., Gloer, A., Gopalswamy, N., Grenfell, J.L., Gronoff, G., Güdel, M., Herbst, K., Henning, W.G., Jackman, C.H., Jin, M., Johnstone, C.P., Kaltenegger, L., Kay, C.D., Kobayashi, K., Kuang, W., Li, G., Lynch, B.J., Lüftinger, S., Luhmann, J.G., Maehara, H., Mlynczak, M.G., Notsu, Y., Osten, R.A., Ramirez, R.M., Scheucher, M., Schlieder, J.E., Shibata, K., Sousa-Silva, C., Stamenković, V., Strangeway, R.J., Usmanov, A.V., Vergados, P., Verkhoglyadova, O.P., Vidal, A.A., Voytek, M., Way, M.J., Zank, G.P., Yamashiki, Y.: 2020, Impact of space weather on climate and habitability of terrestrial-type exoplanets. Int. J. Astrobiol. 19, 136. DOI. ADS.

Aller, A., Lillo-Box, J., Jones, D., Miranda, L.F., Barceló Forteza, S.: 2020, Planetary nebulae seen with TESS: discovery of new binary central star candidates from Cycle 1. Astron. Astrophys. 635, A128. DOI. ADS.

Anfinogentov, S., Nakariakov, V.M., Mathioudakis, M., Van Doorsselaere, T., Kowalski, A.F.: 2013, The decaying long-period oscillation of a stellar megaflare. Astrophys. J. 773, 156. DOI. ADS.

Astraatmadja, T.L., Bailer-Jones, C.A.L.: 2016, Estimating distances from parallaxes. II. Performance of Bayesian distance estimators on a Gaia-like catalogue. Astrophys. J. 832, 137. DOI. ADS.

Balona, L.A., Broholm, A.-M., Kosovichev, A., Nakariakov, V.M., Pugh, C.E., Van Doorsselaere, T.: 2015, Oscillations in stellar superflares. Mon. Not. Roy. Astron. Soc. 450, 956. DOI. ADS.

Broholm, A.-M., Davenport, J.R.A., Hayes, L.A., Inglis, A.R., Kolotkov, D.Y., McLauglin, J.A., Mehta, T., Nakariakov, V.M., Notsu, Y., Pascoe, D.J., Pugh, C.E., Van Doorselaere, T.: 2019, A blueprint of state-of-the-art techniques for detecting quasi-periodic pulsations in solar and stellar flares. Astrophys. J. Suppl. 244, 44. DOI. ADS.

Caspi, A., Krucker, S., Lin, R.P.: 2014, Statistical properties of super-hot solar flares. Astrophys. J. 781, 43. DOI. ADS.

Cho, I.-H., Cho, K.-S., Nakariakov, V.M., Kim, S., Kumar, P.: 2016, Comparison of damped oscillations in solar and stellar X-ray flares. Astrophys. J. 830, 110. DOI. ADS.

Cohen, O., Attrill, G.D.R., Schwadron, N.A., Crooker, N.U., Owens, M.J., Downs, C., Gombosi, T.I.: 2010, Numerical simulation of the 12 May 1997 CME event: the role of magnetic reconnection. J. Geophys. Res. 115, A10104. DOI. ADS.

Cohen, O., Yadav, R., Garraffo, C., Saar, S.H., Wolk, S.J., Kashyap, V.L., Drake, J.J., Pilitteri, I.: 2017, Giant coronal loops dominate the quiescent X-ray emission in rapidly rotating M stars. Astrophys. J. 834, 14. DOI. ADS.

Davenport, J.R.A.: 2016, appaloosa: Python-based flare finding code for Kepler light curves. ADS.

Davenport, J.R.A., Covey, K.R., Clarke, R.W., Boeck, A.C., Cornet, J., Hawley, S.L.: 2019, The evolution of flare activity with stellar age. Astrophys. J. 871, 241. DOI. ADS.

Diamond-Lowe, H., Youngblood, A., Charbonneau, D., King, G., Teal, D.J., Bastelberger, S., Corrales, L., Kempton, E.M.-R.: 2021, The high-energy spectrum of the nearby planet-hosting inactive mid-M dwarf LHS 3844. Astron. J. 162, 10. DOI. ADS.

Doyle, L., Ramsay, G., Doyle, J.G.: 2020, Superflares and variability in solar-type stars with TESS in the southern hemisphere. Mon. Not. Roy. Astron. Soc. 494, 3596. DOI. ADS.
Stoev, H., Suess, F.F., Surdej, J., Szabados, L., Szegedi-Elek, E., Tapiador, D., Taris, F., Tauran, G., Taylor, M.B., Teixeira, R., Terrett, D., Teyssandier, P., Thuillot, W., Titarenko, A., Torra Clotet, F., Turon, C., Ulla, A., Utrilla, E., Uzzi, S., Vaillant, M., Valentini, G., Valette, V., van Elteren, A., Van Helmer- ryck, E., van Leeuwen, M., Vascotto, M., Vecchiato, A., Veljanoski, J., Viaña, Y., Vicente, D., Vogt, S., von Essen, C., Voss, H., Votruba, V., Voutsinas, S., Walmsley, G., Weiler, M., Wertz, O., Wevers, T., Wyzzykowska, Ł., Yoldas, Ž., Žerjal, M., Ziaeepour, H., Zorec, J., Zschocke, S., Zucker, S., Zurbach, C., Zwitter, T.: 2018, Gaia data release 2: Summary of the contents and survey properties. Astron. Astrophys. 616, A1. DOI. ADS.

Gillon, M., Traud, A.H.M., Demory, B.-O., Jehin, E., Agol, E., Deck, K.M., Lederer, S.M., de Wit, J., Burdanov, A., Inglis, J.G., Bolmont, E., Leconte, J., Raymond, S.N., Selsis, F., Turbet, M., Barkaoui, K., Burgasser, A., Burleigh, M.R., Carey, S.J., Chaushev, A., Copperwheat, C.M., Delrez, L., Fernandes, C.S., Holdsworth, D.L., Kotze, E.J., Van Grootel, V., Almleaky, Y., Benkhaldoun, Z., Magain, P., Queloz, D.: 2017, Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1. Nature 542, 456. DOI. ADS.

Günther, M.N., Zhan, Z., Seager, S., Rimmer, P.B., Ranjan, S., Stassun, K.G., Oelkers, R.J., Daylan, T., Newton, E., Kristiansen, M.H., Ohl, K., Gillen, E., Rappaport, S., Ricker, G.R., Vanderspek, R.K., Latham, D.W., Winn, J.N., Jenkins, J.M., Glidden, A., Fausing, M., Levine, A.M., Dittmann, J.A., Quinn, S.N., Krishnamurthy, A., Tingley, E.B.: 2020, Stellar flares from the first TESS data release: exploring a new sample of M dwarfs. Astron. J. 159, 60. DOI. ADS.

Hardegree-Ullman, K.K., Cushing, M.C., Muirhead, P.S., Christiansen, J.L.: 2019, Kepler planet occurrence rates for mid-type M dwarfs as a function of spectral type. Astron. J. 158, 75. DOI. ADS.

Hartman, J.D., Bakos, G.A.: 2016, VARTOOLS: a program for analysing astronomical time-series data. Astron. Comput. 17, 1. DOI. ADS.

Hayes, L.A., Gallagher, P.T., McCauley, J., Dennis, B.R., Ireland, J., Inglis, A.: 2017, Pulsations in the Earth’s lower ionosphere synchronized with solar flare emission. J. Geophys. Res. 122, 9841. DOI. ADS.

Hayes, L.A., Inglis, A., Christie, S., Dennis, B., Gallagher, P.T.: 2020, Statistical study of GOES X-ray quasi-periodic pulsations in solar flares. Astrophys. J. 895, 50. DOI. ADS.

Hedges, C., Lugger, R., Dotson, J., Foreman-Mackey, D., Barentsen, G.: 2021, Multiwavelength photometry derived from monochromatic Kepler data. Astron. J. 161, 95. DOI. ADS.

Howard, W.S., Corbett, H., Law, N.M., Ratzloff, J.K., Glazier, A., Fors, O., del Ser, D., Haislip, J.: 2019, EryvFlare. I. Long-term eryvscope monitoring of flares from the cool stars across half the southern sky. Astrophys. J. 881, 9. DOI. ADS.

Huang, N.E., Shen, Z., Long, S.R., Wu, M.C., Shih, H.H., Zheng, Q., Yen, N.-C., Triaud, A.H.M.J., Demory, B.-O., Hedges, C., Luger, R., Foreman-Mackey, D., Barentsen, G.: 2018, VARTOOLS: a program for analysing astronomical time-series data. Astron. Comput. 17, 1. DOI. ADS.

Ip, W.-H., Kopp, A., Hu, J.-H.: 2004, On the star-magnetosphere interaction of close-in exoplanets. Astrophys. J. Lett. 602, L53. DOI. ADS.

Jackman, J.A.G., Shkolnik, E., Loyd, R.O.P.: 2021, Stellar flares from blended and neighbouring stars in Kepler short cadence observations. Mon. Not. Roy. Astron. Soc. 502, 2033. DOI. ADS.

Jackman, J.A.G., Wheatley, P.J., Pugh, C.E., Kolotkov, D.Y., Broomhall, A.-M., Kennedy, G.M., Murphy, S.J., Raddi, R., Burleigh, M.R., Casewell, S.L., Eigen Müller, P., Gillen, E., Günther, M.N., Jenkins, J.S., Louden, T., McCormac, J., Raynard, L., Poppenhaeger, K., Udry, S., Watson, C.A., West, R.G.: 2019, Detection of a giant flare displaying quasi-periodic pulsations from a pre-main-sequence M star by the Next Generation Transit Survey. Mon. Not. Roy. Astron. Soc. 482, 5553. DOI. ADS.

Kolotkov, D.Y., Anfinogentov, S.A., Nakariakov, V.M.: 2016, Empirical mode decomposition analysis of random processes in the solar atmosphere. Astron. Astrophys. 592, A153. DOI. ADS.

Kopparapu, R.K., Ramirez, R., Kasting, J.F., Eymet, V., Robinson, T.D., Mahadevan, S., Terrien, R.C., Domagal-Goldman, S., Meadows, V., Deshpande, R.: 2013, Habitable zones around main-sequence stars: new estimates. Astrophys. J. 765, 131. DOI. ADS.

Kopparapu, R.K., Ramirez, R.M., SchottelIotte, J., Kasting, J.F., Domagal-Goldman, S., Eymet, V.: 2014, Habitable zones around main-sequence stars: dependence on planetary mass. Astrophys. J. Lett. 787, L29. DOI. ADS.

Kowalski, A.F., Mathioudakis, M., Hawley, S.L., Wisniewski, J.P., Dhillon, V.S., Marsh, T.R., Hilton, E.J., Brown, B.P.: 2016, M dwarf flare continuum variations on one-second timescales: calibrating and modeling of ULTRACAM flare color indices. Astrophys. J. 820, 95. DOI. ADS.

Kupriyanova, E., Kolotkov, D., Nakariakov, V., Kaufman, A.: 2020, Quasi-periodic pulsations in solar and stellar flares. Review. J. Solar-Terr. Phys. 6, 3. DOI. ADS.

Lightkurve Collaboration, Cardoso, J.V.d.M., Hedges, C., Gully-Santiago, M., Saunders, N., Cody, A.M., Barclay, T., Hall, O., Sagear, S., Turtelboom, E., Zhang, J., Tzanidakis, A., Mighell, K., Coughlin, J., Bell, K., Berta-Thompson, Z., Williams, P., Dotson, J., Barentsen, G.: 2018, Lightkurve: Kepler and TESS time series analysis in Python, Astrophysics Source Code Library. ADS.
Maehara, H., Shibayama, T., Notsu, S., Notsu, Y., Nagao, T., Kusaba, S., Honda, S., Nogami, D., Shibata, K.: 2012, Superflares on solar-type stars. Nature 485, 478. DOI. ADS.

Maehara, H., Shibayama, T., Notsu, Y., Notsu, S., Honda, S., Nogami, D., Shibata, K.: 2015, Statistical properties of superflares on solar-type stars based on 1-min cadence data. Earth Planets Space 67, 59. DOI. ADS.

Mathioudakis, M., Bloomfield, D.S., Jess, D.B., Dhillon, V.S., Marsh, T.R.: 2006, The periodic variations of a white-light flare observed with ULTRACAM. Astron. Astrophys. 456, 323. DOI. ADS.

McLaughlin, J.A., Nakariakov, V.M., Dominique, M., Jelínek, P., Takasao, S.: 2018, Modelling quasi-periodic pulsations in solar and stellar flares. Space Sci. Rev. 214, 45. DOI. ADS.

Melbourne, K., Youngblood, A., France, K., Froning, C.S., Pineda, J.S., Shkolnik, E.L., Wilson, D.J., Wood, B.E., Basu, S., Roberge, A., Schlieder, J.E., Cauley, P.W., Loyd, R.O.P., Newton, E.R., Schneider, A., Arulanantham, N., Berta-Thompson, Z., Brown, A., Buccino, A.P., Kempton, E., Linsky, J.L., Logsdon, S.E., Mauas, P., Pagano, I., Peacock, S., Redfield, S., Rugheimer, S., Schneider, P.C., Teal, D.J., Tian, F., Tilipman, D., Vievies, M.: 2020, Estimating the ultraviolet emission of M dwarfs with exoplanets from Ca II and Hα. Astron. J. 160, 269. DOI. ADS.

Mitra-Kraev, U., Harra, L.K., Williams, D.R., Kraev, E.: 2005, The first observed stellar X-ray flare oscillation: constraints on the flare loop length and the magnetic field. Astron. Astrophys. 436, 1041. DOI. ADS.

Monsignori Fossi, B.C., Landini, M., Del Zanna, G., Bowyer, S.: 1996, A time-resolved extreme-ultraviolet spectroscopic study of the quiescent and flaring corona of the flare star AU microscopii. Astrophys. J. 466, 427. DOI. ADS.

Morin, J., Donati, J.-F., Petit, P., Delfosse, X., Forveille, T., Albert, L., Aurière, M., Cabanac, R., Dintrans, B., Fares, R., Gastine, T., Jardine, M.M., Lignières, F., Paletou, F., Ramirez Velez, J.C., Théado, S.: 2008, Large-scale magnetic topologies of mid M dwarfs. Mon. Not. Roy. Astron. Soc. 390, 567. DOI. ADS.

Mullan, D.J., Mathioudakis, M., Bloomfield, D.S., Christian, D.J.: 2006, A comparative study of flaring loops in active stars. Astrophys. J. Suppl. 164, 173. DOI. ADS.

Murasu, K., Uosokin, I.G., Maris, G.: 2007, Introduction to space climate. Adv. Space Res. 40, 885. DOI. ADS.

Nakariakov, V.M., Kolotkov, D.Y.: 2020, Magnetohydrodynamic waves in the solar corona. Annu. Rev. Astron. Astrophys. 58, 441. DOI. ADS.

Nakariakov, V.M., Foullon, C., Verwichte, E., Young, N.P.: 2006, Quasi-periodic modulation of solar and stellar flaring emission by magnetohydrodynamic oscillations in a nearby loop. Astron. Astrophys. 452, 343. DOI. ADS.

Nakariakov, V.M., Kosak, M.K., Kolotkov, D.Y., Anfinogentov, S.A., Kumar, P., Moon, Y.-J.: 2019, Properties of slow magnetoacoustic oscillations of solar coronal loops by multi-instrumental observations. Astrophys. J. Lett. 874, L1. DOI. ADS.

Namekata, K., Sakaue, T., Watanabe, K., Asai, A., Maehara, H., Notsu, Y., Notsu, S., Honda, S., Ishii, T.T., Ikuta, K., Nogami, D., Shibata, K.: 2017, Statistical studies of solar white-light flares and comparisons with superflares on solar-type stars. Astrophys. J. 851, 91. DOI. ADS.

Nandy, D., Martens, P.C.H., Obridko, V., Dash, S., Georgieva, K.: 2021, Solar evolution and extrema: current state of understanding of long-term solar variability and its planetary impacts. Prog. Earth Planet. Sci. 8, 40. DOI. ADS.

Nina, A., Čadež, V.M.: 2013, Detection of acoustic-gravity waves in lower ionosphere by VLF radio waves. Geophys. Res. Lett. 40, 4803. DOI. ADS.

Notsu, Y., Maehara, H., Honda, S., Hawley, S.L., Davenport, J.R.A., Namekata, K., Notsu, S., Ikuta, K., Nogami, D., Shibata, K.: 2019, Do Kepler superflare stars really include slowly rotating sun-like stars?—results using APO 3.5 m telescope spectroscopic observations and Gaia-DR2 data. Astrophys. J. 876, 58. DOI. ADS.

NRC: 2008, Severe Space Weather Events: Understanding Societal and Economic Impacts: A Workshop Report, The National Academies Press, Washington. 978-0-309-12769-1. DOI.

Osten, R.A., Bastian, T.S.: 2006, Wide-band spectroscopy of two radio bursts on AD Leonis. Astrophys. J. 637, 1016. DOI. ADS.

Osten, R.A., Bastian, T.S.: 2008, Ultrahigh time resolution observations of radio bursts on AD Leonis. Astrophys. J. 674, 1078. DOI. ADS.

Pecaut, M.J., Mamajek, E.E.: 2013, Intrinsic colors, temperatures, and bolometric corrections of pre-main-sequence stars. Astrophys. J. Suppl. 208, 9. DOI. ADS.

Pugh, C.E., Broomhall, A.-M., Nakariakov, V.M.: 2017, Significance testing for quasi-periodic pulsations in solar and stellar flares. Astron. Astrophys. 602, A47. DOI. ADS.

Pugh, C.E., Armstrong, D.J., Nakariakov, V.M., Broomhall, A.-M.: 2016, Statistical properties of quasi-periodic pulsations in white-light flares observed with Kepler. Mon. Not. Roy. Astron. Soc. 459, 3659. DOI. ADS.
Rajpaul, V., Aigrain, S., Osborne, M.A., Reece, S., Roberts, S.: 2015, A Gaussian process framework for modelling stellar activity signals in radial velocity data. *Mon. Not. Roy. Astron. Soc.* **452**, 2269. DOI. ADS.

Ramsay, G., Doyle, J.G., Doyle, L.: 2020, TESS observations of southern ultrafast rotating low-mass stars. *Mon. Not. Roy. Astron. Soc.* **497**, 2320. DOI. ADS.

Reale, F., Lopez-Santiago, J., Flaccomio, E., Petralia, A., Sciortino, S.: 2018, X-ray flare oscillations track plasma sloshing along star-disk magnetic tubes in the Orion star-forming region. *Astrophys. J.* **856**, 51. DOI. ADS.

Reiners, A.: 2012, Observations of cool-star magnetic fields. *Liv. Rev. Solar Phys.* **9**, 1. DOI. ADS.

Rimmer, P.B., Xu, J., Thompson, S.J., Gillen, E., Sutherland, J.D., Queloz, D.: 2018, The origin of RNA precursors on exoplanets. *Sci. Adv.* **4**, eaar3302. DOI. ADS.

Roberts, B., Edwin, P.M., Benz, A.O.: 1984, On coronal oscillations. *Astrophys. J.* **279**, 857. DOI. ADS.

Schmitt, J.H.M.M., Ioannidis, P., Robrade, J., Czesla, S., Schneider, P.C.: 2019, Superflares on AB Doradus observed with TESS. *Astron. Astrophys.* **628**, A79. DOI. ADS.

Shibata, K., Isobe, H., Hillier, A., Choudhuri, A.R., Maehara, H., Ishii, T.T., Shibayama, T., Notsu, S., Notsu, Y., Nagoa, T., Honda, S., Nogami, D.: 2013, Can superflares occur on our Sun? *Publ. Astron. Soc. Japan* **65**, 49. DOI. ADS.

Skumanich, A.: 1986, Some evidence on the evolution of the flare mechanism in dwarf stars. *Astrophys. J.* **309**, 858. DOI. ADS.

Stassun, K.G., Oelkers, R.J., Paegert, M., Torres, G., Pepper, J., De Lee, N., Collins, K., Latham, D.W., Muirhead, P.S., Chittidi, J., Rojas-Ayala, B., Fleming, S.W., Rose, M.E., Tenenbaum, P., Ting, E.B., Kane, S.R., Barclay, T., Winn, J.N., Vanderspek, R., Sasselov, D., Seager, S., Sharma, S., Shiao, B., Sozzetti, A., Stello, D., Vanderspek, R., Wallace, G., Winn, J.N.: 2019, The revised TESS input catalog and candidate target list. *Astron. J.* **158**, 138. DOI. ADS.

Strugarek, A., Brun, A.S., Matt, S.P., Réville, V.: 2014, On the diversity of magnetic interactions in close-in star-planet systems. *Astrophys. J.* **795**, 86. DOI. ADS.

Tilley, M.A., Segura, A., Meadows, V., Hawley, S., Davenport, J.: 2019, Modeling repeated M dwarf flaring at an Earth-like planet in the habitable zone: atmospheric effects for an unmagnetized planet. *Astrobiology* **19**, 64. DOI. ADS.

Tu, Z.-L., Yang, M., Zhang, Z.J., Wang, F.Y.: 2020, Superflares on solar-type stars from the first year observation of TESS. *Astrophys. J.* **890**, 46. DOI. ADS.

Van Doorsselaere, T., Kupriyanova, E.G., Yuan, D.: 2016, Quasi-periodic pulsations in solar and stellar flares: an overview of recent results (invited review). *Solar Phys.* **291**, 3143. DOI. ADS.

Vaughan, S.: 2005, A simple test for periodic signals in red noise. *Astron. Astrophys.* **431**, 391. DOI. ADS.

Vida, K., Oláh, K., Kővári, Z., van Driel-Gesztelyi, L., Moór, A., Pál, A.: 2019, Flaring activity of Proxima Centauri from TESS observations: quasi-periodic oscillations during flare decay and inferences on the habitability of Proxima b. *Astrophys. J.* **884**, 160. DOI. ADS.

Zimovets, I.V., McLaughlin, J.A., Srivastava, A.K., Kolotkov, D.Y., Kuznetsov, A.A., Kupriyanova, E.G., Cho, I.-H., Inglis, A.R., Reale, F., Pascoe, D.J., Tian, H., Yuan, D., Li, D., Zhang, Q.M.: 2021, Quasi-periodic pulsations in solar and stellar flares: a review of underpinning physical mechanisms and their predicted observational signatures. *Space Sci. Rev.* **217**, 66. DOI. ADS.
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