Superflares and variability in solar-type stars with TESS in the Southern hemisphere

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ABSTRACT
Superflares on solar-type stars have been a rapidly developing field ever since the launch of Kepler. Over the years, there have been several studies investigating the statistics of these explosive events. In this study, we present a statistical analysis of stellar flares on solar-type stars made using photometric data in 2-min cadence from Transiting Exoplanet Survey Satellite of the whole Southern hemisphere (sectors 1–13). We derive rotational periods for all the stars in our sample from rotational modulations present in the light curve as a result of large star-spot(s) on the surface. We identify 1980 stellar flares from 209 solar-type stars with energies in the range of $10^{31}–10^{36}$ erg (using the solar flare classification, this corresponds to X1–X100 000) and conduct an analysis into their properties. We investigate the rotational phase of the flares and find no preference for any phase, suggesting the flares are randomly distributed. As a benchmark, we use GOES data of solar flares to detail the close relationship between solar flares and sunspots. In addition, we also calculate approximate spot areas for each of our stars and compare this to flare number, rotational phase, and flare energy. Additionally, two of our stars were observed in the continuous viewing zone with light-curves spanning 1 yr; as a result we examine the stellar variability of these stars in more detail.

Key words: stars: activity – stars: flare – stars: magnetic field – stars: solar-type.

1 INTRODUCTION
Solar flares are powerful, eruptive events that are seen across the entire electromagnetic spectrum. They result from a build-up of magnetic energy that is converted into kinetic energy, thermal energy, and particle acceleration through magnetic reconnection, where the magnetic field simplifies. Overall, our Sun can show flares with energy outputs ranging from $10^{24}$ to $10^{32}$ erg (Aschwanden et al. 2000). However, studies of solar-type stars using Kepler have revealed flares with energies exceeding $10^{32}$ erg, with ‘superflares’ having energies up to $10^{38}$ erg (Schaefer, King & Deliyannis 2000).

During its lifetime (2009–2018), the Kepler mission (Borucki et al. 2010) provided a wealth of photometric light curves for hundreds of thousands of stars. This allowed for the study of stellar activity from the interior to the photosphere in a large selection of stars from solar-type to low-mass stars.

Maehara et al. (2012) conducted the first statistical study of flares on solar-type (G-type main-sequence) stars. They used Kepler long-cadence (LC: 30-min) light curves and identified 365 superflares (flares with energies $>10^{33}$ erg) on 148 G-type stars. In addition, they fit the occurrence distribution rate of the flares with a power law and find it is similar to solar flares and flares on low-mass stars. They also explore the proposed theory of hot Jupiters being important in the generation of superflares (Rubenstein & Schaefer 2000) and find none have been discovered around their sample of solar-type stars, indicating they are rare. Lastly, using derived rotation periods for each star they conclude superflares occur more frequently on young solar-type stars (younger than our Sun) as a result of faster rotation periods.

In Shibayama et al. (2013), they extend the work started by Maehara et al. (2012), searching for superflares on solar-type stars (G-type dwarfs) with Kepler LC data over a longer period of 500 d. This resulted in identifying 1547 superflares on 279 solar-type stars, increasing the sample of flares by a factor of 4. Overall, they confirm the previous results, identifying the distribution of occurrence rate as a function of energy to be similar to that of solar flares. Interestingly, by monitoring the brightness variation of their sample they conclude the high occurrence of superflares could be a result of extremely large star-spots.

More recently, Notsu et al. (2019) presented a complete review of Kepler solar-type superflares, including updates on a new sample using the Apache Point Observatory (APO) and Gaia Data Release 2 (DR2). The results from Gaia DR2 revealed the possibility of contamination of subgiant stars within the classification of Kepler solar-type stars. This is due to previous classifications using $T_{\text{eff}}$ and log($g$) values from the Kepler Input Catalog (KIC; Brown et al. 2011) where there are large differences between real and catalogued...
values. One of the other key differences was their ability to check theinarity of their new sources using APO spectroscopic observations,
ruling out stars that were members of binary systems. This in turn
rules out the generation of flares as a result of magnetic interaction
between the binary system. They also investigate star-spot size,
concluding the majority of superflares occur on stars with larger
star spots; however, they acknowledge there is some scatter. With
regards to rotation period ($P_{\text{rot}}$), they note maximum spot size does
not depend on $P_{\text{rot}}$, but maximum flare energy does continuously
decrease with slower rotation.

In solar physics, the relationship between flares and sunspots has been well established, with these phenomena being closely linked. Multiple studies, such as Maehara et al. (2012, 2017) and Notsu et al. (2013, 2019), of solar-type stars report close links between star-spots and flaring activity concluding superflares are a result of stored magnetic energy near star-spots. Despite this, the relationship between flare rotational phase and star-spots in solar-type stars has not been investigated in great detail. Large variations in brightness seen in light curves, also known as rotational modulation, are attributed to be the result of star-spots on the stellar disc moving in and out of view as the star rotates (Rodono et al. 1986; Oláh et al. 1997). If superflares do occur near star-spots due to the storage of magnetic energy, then you would expect to see a correlation between star-spots and flare occurrence.

In our previous studies, Doyle et al. (2018, 2019) (henceforth Papers I and II, respectively), we used K2 and Transiting Exoplanet Survey Satellite (TESS) short-cadence (SC) photometric data to investigate the rotational phase of flares in a sample of 183 M dwarfs. By using simple statistical tests, we determined the phase distribution of the flares was random and did not coincide with the large star-spot producing the rotational modulation. This result came as a surprise as it suggests the flares on these M dwarf stars are not correlated with the dominant large star-spot present on the stellar disc. As a result, this indicates the magnetic field and resulting activity on these stars may be more complex than what is observed on the Sun.

In this study, we use TESS 2-min photometric light curves from a sample of solar-type stars observed in sectors 1–13 to conduct a statistical analysis of their flaring properties where the SC 2-min TESS data are important for detecting low-energy, short-duration flares. In addition to investigating the rotation periods, flare energies, and flare frequency, we will explore the rotational phase of the flares. This analysis aims to determine whether the flares and star-spots on these solar-type stars share the same strong correlation as solar flares and sunspots on the Sun. Furthermore, we will use historic GOES data of solar flares to investigate the relationship between solar flares and sunspots in greater detail.

2 SOLAR-TYPE STAR SAMPLE

In previous solar-type star studies, the sources were identified using their effective temperatures ($T_{\text{eff}}$) and $\log(g)$ values from the KIC, or other associated catalogues. However, this process led to a contamination of subgiants within the sample that were incorrectly identified due to differences between real (Gaia DR2) and catalogued values. Here, we identify solar-type stars as those with spectral types ranging from F7 to K2 according to the SIMBAD catalogue, and have been observed in 2-min cadence by TESS.

We now go on to discuss the various steps that were taken to eliminate any sources that were not main-sequence solar-type stars. First, the sources were cross-referenced with the SkyMapper Southern Sky Survey (Wolf et al. 2018) and Gaia DR2 (Gaia Collaboration 2018). Any star that did not possess SkyMapper magnitudes or Gaia parallaxes was not considered any further. We use radii and luminosity values from Gaia DR2 to eliminate any that are likely to be giants and hence wrongly classified within SIMBAD. We use Skymapper multicolour magnitudes and Gaia parallaxes to determine the quiescent luminosity of the stars in the TESS bandpass. The magnitudes in the $g$, $r$, $i$, and $z$ bands are converted to flux and then fitted by a polynomial to produce template spectra of each star. These are then convolved by the TESS bandpass providing the quiescent flux of each star in the TESS bandpass. By inverting the Gaia parallaxes, we determine the distances of our sample and use them to infer the quiescent luminosity of each star. The Gaia parallaxes for our sample are all much larger than their errors, so we do not expect spurious solutions as outlined in Arenou et al. (2018). These values along with the stellar properties of each star are provided in Table 1.

The TESS 2-min light curves of the remaining sources were visually inspected by eye individually to determine those that showed any signs of rotational modulation. Some sources that showed complex light curves or no evidence of rotational modulation were not considered further. Only a handful of these sources that did not possess rotational modulation showed any evidence of flaring activity and were omitted as the rotational period is a key aspect of our analysis. Finally, all light curves were then run through a flare finding algorithm (see Section 4.2 for more details) and any that did not show any flaring activity were omitted from further analysis. This process resulted in a final sample of 209 solar-type stars observed in 2-min cadence by TESS. The spread of spectral types within this sample is shown in Fig. 1. Additionally, it is important to note three of the stars within our sample show evidence of belonging to an eclipsing binary in the TESS light curves. We will discuss this further in Section 9.

Due to the nature of the selection of targets for our solar-type sample there are some selection biases that should be highlighted. First, only stars that had spectral types recorded in SIMBAD were initially selected: we are therefore biased towards stars that had a spectral type recorded. Secondly, only those stars that display rotational modulation are selected, as it is critical for our analysis. However, this results in a bias towards active solar-type stars in our sample meaning a complete picture is not achieved. Additionally, there is a bias towards later-type (G8–K2) solar-type stars, see Fig. 1. Finally, targets had to possess SkyMapper and Gaia data which resulted in some targets being omitted from this study that potentially could have shown rotational modulation and/or flares. Despite these selection biases, we consider that our final sample of 209 solar-type stars with spectral types between F7 and K2 (for the full stellar properties see Table 1) is large enough for determining the rate of superflares from solar-type stars and whether they show any rotational phase dependence.

3 TESS PHOTOMETRIC LIGHT CURVES

The TESS (Ricker et al. 2015) was launched in 2018 April. During its initial 2-yr mission, TESS will make a near all-sky survey observing 200000 of the closest stars to our Sun. TESS is fitted with four CCD cameras which act as a $1 \times 4$ array providing a total FOV of 24 deg $\times$ 96 deg. Each of the hemispheres are split into 13 equal sectors that TESS will observe for a duration of 27.4 d each. Close to
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As mentioned in our paper HD 42270 261236136 1, 12, and 13 88.37 −

CD-52 10232 161172848 1 339.87 −52.08 2 K0 10.03 9.42 106.1 4.25 32.82 32.82–35.06 8.0–232.0

The primary mission for TESS is to search for exoplanets via the Kepler transit method around low-mass M dwarf stars. Therefore, TESS has a bandpass of 600–1000 nm and is centred on 786.5 nm (Ricker et al. 2015) making it slightly redder in comparison to Kepler. This redder bandpass allows TESS to observe a larger number of M dwarfs making planets easier to detect. As mentioned in our paper (Doyle et al. 2019), the TESS bandpass is more sensitive to redder wavelengths, meaning it will not detect less energetic flares as they typically have their peak emission towards the blue. Overall, the rms of the TESS light curves for M dwarfs of the same magnitude is 4.6 times lower than the Kepler light curves. As a result, TESS will be unable to detect short duration, low amplitude flares (Ramsay, Doyle & Doyle 2020); however, this is related to the brightness of the stars where lower energy flares could be detected on brighter targets. Overall, the key factor in detecting low-energy flares is the SNR of the light curve.

In this paper, we will use photometric light curves of solar-type stars from sectors 1 to 13 made between 2018 July 25th and 2019 July 18th. We downloaded the calibrated light curve for each of our target stars from the MAST data archive. We used the data values for PDCSAP_FLUX, which are the Simple Aperture Photometry values, SAP_FLUX, after the removal of systematic trends common to all stars in that Chip. Each photometric point is assigned a QUALITY flag that indicates if the data may have been compromised to some degree by instrumental effects. We removed those points that did not have QUALITY = 0 and normalized each light curve by dividing the flux of each point by the mean flux of the star. Overall, 158 solar-type stars in the sample (76 per cent) were observed in only one sector with the remaining 58 (24 per cent) targets being observed in multiple sectors. The full details of how many sectors each star was observed in can be found in Table 1.

4 STELLAR AND FLARE PROPERTIES

In this section, we will look at both the stellar and flare properties of each star. This includes determining the rotation period, identifying the flares, and calculating their energies. In addition, we will also look further into a small group of ultrafast rotators identified within our solar-type sample.

4.1 Rotation period

We determine rotation periods for all 209 solar-type stars in our sample using the rotational modulation observed in the light curve. This rotational modulation occurs as a result of large, dominant star spots that move in and out of view as the star rotates, changing the brightness of the star periodically. Examples of this phenomenon can be seen in Fig. 2 of several solar-type stars ranging in rotation period and spectral type.

To determine the rotation periods, \( P_{\text{rot}} \), we utilize a Lomb–Scargle (LS) periodogram from the software package VARTOOLS (Hartman & Bakos 2016). This provides an initial estimation of \( P_{\text{rot}} \), and by phase folding and binning the light curve through an iterative process, a final value is verified. Along with \( P_{\text{rot}} \) phase zero, \( \phi_0 \), is also determined and represents the minimum of the flux of the rotational modulation. Overall, this process allows for the determination of both \( P_{\text{rot}} \) and \( \phi_0 \), which is used in subsequent analysis of the magnetic activity. Errors on \( P_{\text{rot}} \) are estimated to be within a few per cent. It is important to note that occasionally the LS periodogram detects half of the true period. However, as we have visually inspected each light curve we can usually identify instances where this has occurred and modify the period accordingly. We therefore do not consider that many stars have incorrect periods.

https://archive.stsci.edu/tess/
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Figure 2. Here, we show three examples of light curves from the solar-type stars CD-52 10232 (top), HD 221224 (middle), and BD-19 3018 (bottom). These have spectral types K0, G5, and K0 and rotation periods 4.25, 1.58, and 4.07 d, respectively. As well as clear modulation within these light curves as a result of star spots, flares can also be seen in all three stars.

The stellar properties of the sample can be seen in Table 1 including both $P_{\text{rot}}$ and $\phi_0$. Within our sample rotation periods range from 0.24 to 11.16 d. It is difficult to detect stars with $P_{\text{rot}} > 10$ d (the Sun has $P_{\text{rot}} \sim 27$ d), due to the observation length of TESS at $\sim 27$ d per sector, although for stars with more than one sector of data we can get longer periods. However, despite this, it is still possible to conduct an analysis on this sample in comparison to the Sun as we are comparing the relationship between flares and star spots.

4.2 Stellar flares

We use the same method as Papers I and II to identify the flares present in each light curve and calculate their energies in the TESS bandpass. FBEYE (Davenport et al. 2014) is a suite of IDL programs that scans the light curve, flagging any points which are over a 2.5$\sigma$ threshold. Within the flare finding algorithm, potential flares are required to consist of two or more consecutive flagged points; all of the flares within our sample are composed of many more points and 2 is simply the minimum requirement. Additionally, all flares are visually checked by eye to validate they are indeed flares requiring them to possess a classical flare shape with a sharp rise and exponential decay. Once complete, a comprehensive list of stellar flares including their start and stop times, flux peak and equivalent duration is produced for each star. Some examples of these flares can be seen in Fig. 2 along with the rotational modulation.

The flare numbers for each star can be normalized to give the number of flares per day as the observation length of each star varies as a result of being observed in multiple sectors. In Fig. 3 we plot the normalized flare number alongside the rotational period which shows flare number decreasing with increasing rotation period. Despite the lack of stars with $P_{\text{rot}} > 10$ d, this is consistent with other studies such as Stelzer et al. (2016) but also with Papers I and II.

In addition, we also plot the rotation rate, $\Omega$, as a function of the normalized flare number, see Fig. 3. To do this, we use the relationship $\Omega = 2\pi R/P_{\text{rot}}$ where $R$ is the radius of the star taken from the Gaia DR2 release and $P_{\text{rot}}$ is the rotation period derived earlier. This allows us to identify the fast rotators within the sample. In Paper II, we discovered a group of M dwarf ultrafast rotators (UFRs) with $P_{\text{rot}} < 0.3$ d which surprisingly displayed a low level of flaring activity. Determining ages for these stars did not provide any explanation for their peculiar behaviour. In this sample, we have four solar-type UFRs with $P_{\text{rot}} < 0.4$ d, which also show low levels of flaring activity. At the moment, we do not have a clear explanation for this phenomenon; however, we do believe it is related to the magnetic field properties of the stars. Since these objects are fast rotators, they are probably young, hence it is possible that the flares have their maximum energy in the blue, thus the TESS band-width only sees the more energetic events.

Next we want to determine the energies of the flares within the TESS bandpass. These are calculated as the equivalent duration, area under the flare light curve obtained from FBEYE, multiplied by the quiescent stellar luminosity. As mentioned previously, the quiescent stellar luminosity, $L_{\text{star}}$, was determined from both Skymapper magnitudes and Gaia parallaxes, full details in Section 2. Within the solar-type sample a large variety of flare energies are seen ranging from $2.1 \times 10^{31}$ to $1.8 \times 10^{36}$ erg. Approximately 92 percent of our flare sample are classified as superflares with energies greater than $10^{33}$ erg. It is important to note here the term ‘superflare’ was defined according to the Carrington event that was a X45 class solar flare observed in 1859 and had an energy output of $4.5 \times 10^{32}$ erg (Cliver & Dietrich 2013). Hence, the majority of our flares within the sample exceed this energy range making them ‘superflares’. Similarly, only 1.6 percent of our flare sample have energies less than $10^{32}$ erg, which is the range of solar flares, with no flares less than $10^{31.5}$ erg. This lower limit is due to the effective area of the

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Figure 3. The normalized flares per day of each star in our sample as a function of rotation period, $P_{\text{rot}}$ (top panel) and rotation rate, $\Omega$ (lower panel). Each of the points are colour coded according to the colour bar that represents the maximum flare energy from the star.

TESS telescopes and is also related to the stellar brightness, see Section 3. The highest energy flare of $1.8 \times 10^{36}$ erg was observed on the star HD 217344 (TIC 229066844) a G4 star with $P_{\text{rot}}$ of 1.62 d. All of the flare properties including the minimum flare energy detected (in the online version) for each star can be seen in Table 1, and the spread of flare energies can be seen in Fig. 4.

4.3 Superflare frequency

As well as calculating the flare energies, we want to investigate the frequency of the superflares. Fig. 5 shows the cumulative flare frequency distribution (FFD) of a handful of stars ranging in rotation period and spectral type. The dashed line represents stars with rotation periods less than 2.6 d and a solid line greater than 2.6 d, where 2.6 d represents the median. In addition, stars with varying spectral types are displayed by colour with G1--G4 blue, G5--G9 red, and K0--K2 green, where each line represents an individual star. These stars were selected as they possessed a reasonable number of flares for each of the spectral subtypes and had varying rotational periods. Now, we will go into more detail about the various stars and the relationship between all six as a whole.

First, as an example, the dashed red line represents the G6 type star HD 39150 (TIC 364588501) that has a rotation period of 2.28 d and 207 flares. HD 39150 will produce a flare of energy $10^{35}$ erg approximately every 49 d whereas a flare of $10^{33}$ erg will be produced every 1.5 d. Overall, the higher the flare energy the less frequently it will be observed from the star that is consistent with the mechanism known to generate solar flares on the Sun. Prior to the flare energy release the magnetic field becomes stressed and twisted allowing for the build-up of magnetic energy. The flare is then released as thermal energy, kinetic energy, and particle acceleration when the magnetic field reconfigures and simplifies through magnetic reconnection (and references therein Fletcher et al. 2011). Therefore, it should take longer to build up and store the magnetic energy required for larger energy flares of $10^{35}$ erg and greater, although see Section 4.5 on flare waiting times.

Looking at the slowly rotating stars as a whole, the G9-type star HD 31026 (TIC 077371445; solid red line in Fig. 5) that has a $P_{\text{rot}} = 4.8$ d and a total of 23 flares, shows a higher flare energy than the other slowly rotating stars. Oddly enough, this star was only observed in two sectors in comparison to the other slowly rotating stars at six sectors. From the FFD, we can see it will take...
approximately 150 d for this star to produce another of the highest energy flares that is approximately 5 TESS sectors of observations. Therefore, it could be coincidence that TESS was observing this star at the right time to observe such a large flare.

In terms of the fast rotating stars, HD 39150 (TIC 364588501; mentioned previously) has the highest flare rate and highest energy; however, it was observed in all 13 sectors. The remaining fast rotators both have the same distribution where the difference in spectral type has no effect. As a whole, the behaviour between the fast and slow rotators does change in each of the spectral type groups, where fast rotators show flares more frequently. However, within the G1–G4 spectral group, the flare frequency at lower energies is higher in the slowly rotating star.

Overall, for our small sample the FFD shows the spectral type of the stars does not affect the flare energies. However, it is apparent the rotation period does play a role with the faster rotating stars producing flares of higher energies and flares more frequently. This is to be expected as faster rotating stars tend to produce high energy and overall flare more frequently (with exception of the UFRs) in comparison to their slowly rotating counterparts (Hartmann & Noyes 1987; Maggio et al. 1987).

4.4 Flare effects on habitability

The Sun can produce solar flares with energy outputs of up to $10^{32}$ erg. These explosive events have effects that sweep through the entire Solar system. Due to Mercury’s close proximity with the Sun, its very thin exosphere is constantly being stripped away and then replenished by particles from solar flares, coronal mass ejections, and the solar wind (Guinan & Ribas 2004, and references therein). On Earth, the magnetosphere protects the planet from harmful radiation and fast moving particles that originate from the Sun. In the event of a large X-class solar flare satellites can be disrupted and aurora can be seen at lower latitudes. Gas giant planets such as Jupiter and Saturn have strong internal magnetic fields and large magnetospheres so the effects of flaring activity can result in aurora and geomagnetic storms (Engvold, Vial & Skumanich 2018).

Our sample of 209 solar-type stars was cross-referenced with the NASA Exoplanet Archive3 to identify if any of the targets have known planets. In our sample only one solar-type star, HD 44627 (TIC 260351540), is a host to known exoplanets with a spectral type and rotation period of K1 and 3.9 d. This particular planet is a wide orbiting giant with a semimajor axis of 275 au and mass of 13.5 times Jovian mass and the solar wind (Guinan & Ribas 2004, and references therein). On Earth, the magnetosphere protects the planet from harmful radiation and fast moving particles that originate from the Sun. In the event of a large X-class solar flare satellites can be disrupted and aurora can be seen at lower latitudes. Gas giant planets such as Jupiter and Saturn have strong internal magnetic fields and large magnetospheres so the effects of flaring activity can result in aurora and geomagnetic storms (Engvold, Vial & Skumanich 2018).

We conduct a similar analysis using the solar-type star HD 39150 (TIC 364588501) that shows 207 flares within a year of TESS 2-min cadence observations. Overall, a similar decline in waiting times (Fig. 6a) is observed in comparison with Hawley et al. (2014); however, the range in waiting times is much greater on a scale of days. According to Hudson (2020), there should be a correlation with regards to waiting time and flare magnitude (i.e. energy). However, while some flares with longer waiting times do show higher energies, there is a wide spread amongst waiting time and energy as a whole, see Fig. 6(b). Therefore, this is consistent with HD 39150 possessing multiple active regions on the disc at various stages in the build-up/release of flaring activity. We go on to discuss this in more detail in the subsequent sections.

5 LONG TERM STELLAR VARIABILITY

The continuous viewing zone is an area of the sky where each of the TESS sectors around the poles in the Southern and Northern hemisphere overlap. This produces a region of sky with many stars being observed for approximately 1 yr. In our sample of solar-type stars, we have two which have been observed in the continuous viewing zone, HD 39150 (TIC 364588501) that was observed in all 13 sectors and HD 47875 (TIC 167344043) that was observed in all 13 sectors minus sector 11 where no data were collected. This provides light curves of these stars which span 1 yr allowing us to investigate long-term levels of variability within these stars.

HD 39150 (TIC 364588501) that was observed for a total of 357 d. This G6 star has a rotation period, $P_{\text{rot}} = 2.28$ d and a total of 207 flares with energies reaching $10^{35}$ erg. Fig. 7 shows the light curve of this star spanning approximately 140 d, detailing the changing nature of the rotational modulation. In the bottom left and right-hand panels there is evidence of multiple spots as the shape of the modulation changes. This could be the result of two active regions possessing spots that are rotating with marginally different periods, meaning they are slightly unsynchronized. The whole TESS light curve of this star from all sectors can be folded to one rotation period and phase zero which also suggests this scenario. In addition,
the amplitude of the rotational modulation changes sector to sector suggesting the active regions are growing and decaying as the star rotates or new regions are developing/disappearing. To determine if some of the variability was due to instrumental effects, we examined light curves of spatially nearby stars and found no variation between different sectors. Therefore, we conclude the variability in HD 39150 (TIC 364588501) is intrinsic to the star. With regards to flaring activity, there seems to be an increased level towards the end of this section of light curve between 125 and 155 d where the flares appear more frequently and with a greater energy. Tu et al. (2020) also discuss this target noting the increase in flaring activity within sector 5, however, they do not offer any explanation regarding the reasoning behind this. We discuss this star further later in Section 7.2 providing a potential explanation for the sudden increase in activity while also associating it with the rotational phase distribution of the flares.

HD 47875 (TIC 167344043) is also present within the continuous viewing zone and was observed for a total of 330 d. This star has a spectral type of G4, $P_{\text{rot}}$ of 2.99 d, and a total of 179 flares with energies in the $10^{14}$ erg range. The rotational modulation of this star is constant throughout the year of observations possessing a clear sinusoidal pattern with no evidence of multiple spots. However, the amplitude of this particular star also changes producing a multiperiodic light curve. This would suggest there are potentially migrating spots on the disc of the star, which fall into differential rotation. As a result of this phenomena, large flares are observed as the migrating spot crosses the disc of the star.

Overall, there appears to be more variability observed within solar-type stars on time-scales of months, with regards to their spotted structures, as compared to low-mass stars. We know the active regions and the spot structure observed on the Sun change over periods of weeks to months with no sunspots lasting years. Therefore, it is not unexpected to observe this behaviour in other stars of a similar spectral type. As TESS returns to the southern ecliptic in Cycle 3, follow ups of these stars would be valuable to continue to monitor the changing behaviour observed. This will then lead into long-term observations with the potential to determine stellar cycles which is important in understanding the overall magnetic cycle on other stars.

6 STAR SPOT AREAS

Determining the areas of star spots is a non-trivial process and there are many ways to do so including Zeeman Doppler Imaging (Rosén, Kochukhov & Wade 2015), Spectral Modelling (Fang et al. 2016; Gully-Santiago et al. 2017), and Planet-Transit Spot Modelling (Morris et al. 2017). In addition, it is possible to use the amplitude of the rotational modulation from light curves to provide a rough indication of the approximate areas of star spots on the stellar disc (Rebull et al. 2016a, b; Giles, Collier Cameron & Haywood 2017). However, this process underestimates for the presence of polar spots, circumpolar spots, bands of spots, spots all over the disc, and a pole on star with spot distributions. Despite this, there is still merit in determining star spot areas as it can provide some insight into the conditions needed for these large energy superflares.

In order to determine the star spot area, we will look to use the method described by Notsu et al. (2019). First, we must estimate the temperature of the spot which can be done by applying a relation on the difference between the photosphere and the spot. The relationship is as follows:

$$T_{\text{star}} - T_{\text{spot}} = 3.58 \times 10^{-5} T_{\text{star}}^2 + 0.249 T_{\text{star}} - 808, \quad (1)$$

where $T_{\text{star}}$ is the effective photospheric temperature obtained from Gaia DR2 and $T_{\text{spot}}$ is the temperature of the spot. Next, we use $T_{\text{spot}}$ to calculate the area of the star spot according to the variations within the light curve as follows:

$$A_{\text{spot}} = \frac{\Delta F}{F} A_{\text{star}} \left[ 1 - \left( \frac{T_{\text{spot}}}{T_{\text{star}}} \right)^4 \right]^{-1}, \quad (2)$$

where $\Delta F/F$ is the amplitude of the normalized light curve, which was measured from the phase folded and binned light curve and $A_{\text{star}}$ is the area of the stellar disc calculated as $2\pi R^2$ ($R$ is taken as the Gaia DR2 radius). As an example and benchmark, we calculated the star spot temperature for the Sun, a G2-type solar star with a temperature of $T_{\text{star}} = 5800$ K, finding $T_{\text{spot}} = 3960$ K. This temperature is reasonable and aligns with the temperature range for sunspots at 3500–4550K (Solanki 2003). Using these relationships, we are able to determine approximate spot areas for all 209 solar-type stars within our sample.
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Figure 7. The light curve for HD 39150 (TIC 364588501) covering approximately 170 d detailing the magnetic variability of the star including changing spot structures and flaring.
According to McIntosh (1990), larger more energetic solar flares occur from active regions that host larger spot coverages and complex spot structures. Therefore, we would expect to see the same behaviour within other solar-type stars. In Fig. 8, we look at the stellar spot coverage as a function of rotation period, flare number, and flare energy to investigate whether the predicted behaviour is in fact observed. With regards to rotation period, you would expect a larger spot coverage to result from a faster rotation period. However, in our sample there appears to be no relation and overall there is a large spread in both rotation and spot coverage. This was tested further using the Pearson correlation coefficient (\( P \)) which yielded a result of \( P = -0.13 \) also indicating the lack of any correlation. The Pearson correlation coefficient is a statistical test that measures the linear relationship between two variables. A coefficient of \( P = +1 \) indicates a direct positive linear correlation and \( P = -1 \) a direct negative linear correlation, with \( P = 0 \) indicating no correlation.

Next we look at the number of flares as a function of spot area. The expectation is that the larger the spot coverage the more flares will be observed from the star. However, this is not the case and we observe a peak in flare number at approximately \( 10^{17} \) m\(^2\) where afterwards, there appears to be a drop in flare number for the larger spot coverages. Could this be because these larger spot coverages are producing higher energy flares less frequently? Again, this was tested with the Pearson correlation coefficient providing a value of \( P = -0.05 \) that indicates there is no linear relationship present. This then brings us on to look at the energy of the flares as a function of spot coverage. Although there appears to be some evidence for higher energy flares resulting from larger spot coverages (Fig. 8), the Pearson correlation coefficient provided a result of \( P = 0.38 \) indicating there is a slight significant linear correlation present. Overall, none of the Pearson correlations for any of the plots in Fig. 8 indicate a strong linear correlation.

The solar-type star CPD-5711 31 (TIC 279614617) is a G8-type star that was observed to have the largest star spot coverage despite only having a rotation period of 7.37 d. It was observed in TESS sector 1 and produces two flares during this time. This is a relatively low number considering it has the largest spot coverage of \( 3.8 \times 10^{18} \) m\(^2\) (which equates to 10 per cent of the visible stellar disc) from the solar-type star sample. However, it does produce two of the larger flares with energies in the \( 10^{35} \) erg range.

A similar analysis was conducted by Howard et al. (2019) and Notsu et al. (2019) where they also investigated the spot coverages of their stellar samples against various flare properties. In Howard et al. (2019) they use photometric data from Evryscope (Law et al. 2015) light curves of 113 cool stars to investigate rotation periods, star spot amplitudes and flare properties. They did not find a relationship between the size of the spot coverage and the energy of the flares produced, but were able to constrain the minimum field strength of their late K to mid M flare stars as 0.5 kG. In Notsu et al. (2019), they conduct an investigation into the relationship between superflares and rotation period, including an analysis on the spot coverages of their sample of solar-type (G-type) stars. Overall, they do see a relationship between flare energy and star spot coverage, concluding the superflare energy is in fact related to the star spot coverage of the star. In addition, they also see that superflares tend to occur from stars with shorter rotation periods and larger star spot coverages.

7 ROTATIONAL PHASE

One of the criteria for our sample was the presence of rotational modulation within the TESS light curve. This rotational modulation is the result of star spots that are present on the stellar disc and move in and out of view as the star rotates. In Papers I and II, we test the distribution of flares in samples of M dwarfs using a simple statistical test. Our findings show no evidence for any preference in rotational phase, indicating the flares are randomly distributed. In solar physics there is a well-established relationship between sunspots and solar flares. Therefore, it is surprising to find no such correlation amongst other flare stars.

In this study, we will use the same simple \( \chi^2 \) test to assess the phase distribution of the flares. We will look at the flares from all 209

Figure 8. Here, we show the spot coverage of each star calculated from the amplitude modulation of the TESS light curves as a function of stellar rotation period (top panel), normalized flares per day (middle panel), and maximum flare energy (bottom panel).
Figure 9. A histogram of the rotational phase distribution for all 1980 flares from the sample of 209 solar-type stars. The bin size is $\phi = 0.1$ and the spread shows no preference for any rotational phase. The cut-off for low- and high-energy flares was determined as $10^{34}$ erg.

As mentioned previously there is a large variation in the rotational modulation of the TESS light curves within the solar-type sample caused by the presence of multiple spots. In our sample $\sim$40 per cent show a clear sinusoidal pattern as a result of one star spot structure present on the disc of the star. The remaining 60 per cent show evidence of multiple spot structures that could potentially cause controversy within the rotational phase findings of all flares from all stars. To address this, we remove all stars that show any potential evidence for multiple spot structures and conduct the test on the remaining sample. This consists of 83 solar-type stars with a total of 866 flares. Our results, again, show no preference for rotational phase both in the $\chi^2$ test, KS test, and SW test. Therefore, this strengthens our conclusion that the flares do not originate from the dominant spot/active region but are randomly distributed in rotational phase.

7.2 Individual case studies

We have selected two solar-type stars from our sample which have the highest flare rate and therefore, are ideal candidates to investigate the relationship between rotational phase and flare number. Both of these stars are present in the continuous viewing zone of the TESS mission and their stellar variability was discussed in Section 5. However, in this section, we will only be focusing on the distribution of flares within their light curves as a function of rotational phase. These stars are HD 47875 (TIC 167344043) and HD 39150 (TIC 364588501) with spectral types G4 and G6, flare numbers of 179 and 207 and rotation periods, $P_{\text{rot}}$, of 2.99 and 2.28 d, respectively. We utilized the same simple $\chi^2$ test as discussed previously obtaining values for all low and high as of 1.55, 1.41, and 1.11 for HD 47875 and 0.75, 0.89, and 0.76 for HD 39150. As a result, we find no significant evidence ($>3\sigma$ confidence) of any correlations between rotational phase and flare number.

In Fig. 10, we show the distribution of the flares as a function of their energy along with the phase folded and binned light curves. From these plots, it is easier to see there are flares present at all rotational phases in both high and low energy. In addition, the flares are randomly distributed and there is no preference for any rotational phase even during rotational minimum when the dominant star spot is most visible. Although, there is a hint of increasing high-energy ($>10^{34}$ erg) flares at phase 0.25 and 0.75.

Due to the length of the TESS observations for HD 39150 we want to approach the analysis of flares and rotational phase in a different manner than our previous studies. From Fig. 7, we see that within a few days (e.g. from 137 to 140 d), a large change in the spot structure appears. At $\sim$145 d, we have the presence of a large dominant spot structure while a few days earlier we have the emergence of multiple spots and plage activity which reduces the spot contrast. However, the most interesting aspect is the intense flare activity from 127 to 138 d which clearly indicates a strong link between emerging spots and flare activity. After this point, the star returns to a less active state similar to what is observed at the beginning of the light curve. Chandra et al. (2010) showed that the triggering mechanism for intense flare activity was a combination of flux emergence, shearing between the magnetic polarities of the two flux systems (emerging and pre-existing) plus the interaction of the new emerging bi-poles with pre-existing field. With the spot structure for HD 39150 (TIC 364588501) changing rapidly on a daily basis, intense flare activity is expected.

As a result of this we computed the $\chi^2$ test on the sectors of TESS data for HD 39150 on an individual basis and focused on the period in sectors 5 and 6 which showed the intense flaring...
activity. However, the values for the $\chi^2$ test show no preference for rotational phase. This is to be expected as by looking at the light curve in Fig. 7 during this active period there are flares present at all rotational phases. Despite this, the flares are present as a result of the emergence of multiple spots and plage activity which does suggest the link between spots and flares. However, the spot structures on these stars are more complex than a simple one spot model and so this would be the main reason behind a lack in any clear correlation.

8 THE SOLAR ANALOGUE

With the Sun being our nearest star, astronomers and physicists have been collecting detailed spatial observations to study its phenomena for nearly 150 yr. Similarly, there is a wealth of historic data including sunspot number and flare properties dating back to the 1930s. Overall, these data sources provide a deep knowledge of our closest star aiding in the understanding of multiple solar phenomena and its effects on the Earth and Solar system. In this section, we utilize historic X-ray data of solar flares from the Geostationary Operational Environmental Satellite (GOES) archive and sunspot numbers from the Sunspot Index and Long-term Solar Observations (SILSO) data base to detail the close relationship between solar flares and sunspots.

The relationship between flares and sunspots is well-established and it is generally accepted these phenomena are closely related. Fig. 11(a) sums up this close relationship where the sunspot number (red line) and flare number (blue histogram) are observed to be correlated with each other over the solar cycle. However, despite this, the relationship between sunspots and flares is more complicated than initially believed. In Gao & Zhong (2016), they investigated the temporal behaviour of varying classes of solar flares. Their findings show the lower B-class solar flares to be in antiphase with all other C, M, and X-class solar flares in terms of the solar cycle (see Table 2 for details of the various solar class flares and their respective energies). To investigate this strange behaviour, we plot the solar subclasses as a histogram in Fig. 11(b) which also displays an anticorrelation amongst the A and B-class solar flares. Even more interestingly, the A and B-class flares are also out of synchronization with the sunspot number. These lower energy ($<10^{29}$ erg) solar flares are present when the Sun is in a solar minimum and is considered not very active where there is very little spot coverage. Therefore, these flares could be originating from plage regions or areas where local dynamos are at play. The higher energy ($>10^{29}$ erg) solar flares are then clearly correlated with sunspots and both appear during solar maximum when the Sun is at its most active. As suggested by Gao & Zhong (2016), this anticorrelation within low-class flares could potentially be linked to the negative correlation between small and large sunspots (Nagovitsyn, Pevtsov & Livingston 2012). However, we should note that this result could also be bias due to the systematic effect of non-detection of weak flares when the Sun is bright.

Applying these scenarios to our solar-type star sample could aid in explaining the lack of a correlation between rotational phase and flare number. Lower energy flares are present at all rotational phases (see Fig. 10) that could result from plage, filaments, or local dynamo regions not associated with spots that are present across the
stellar disc. This is similar to what is observed on the Sun where the lower energy flares are predominately present when the Sun is less active and producing a lower number of spotted regions. The lower energy A and B class solar flares are a few orders of magnitude less energetic than those observed on the solar-type sample. However, it is possible to observe flares of energies $10^{28} \text{ erg}$ in solar-type stars, for example using Kepler, see Maehara et al. (2012). Therefore, these lower energy flares could be present but not observable with TESS since it is less sensitive to lower energy flares (see Section 3). As a result, we note our flare sample does not contain any flares with energies less than $10^{28} \text{ erg}$ which equates to a C-class solar flare (see Table 2), however, in our solar-type sample a lower energy flare is considered to be $<10^{34} \text{ erg}$ according to Fig. 4.

Overall, the lower energy ($<10^{34} \text{ erg}$) stellar flares from the solar-type sample could originate from plage, filaments, or local dynamo regions on the stellar disc not associated with star spots. This is similar to the lower energy A and B class solar flares that are also not associated with sunspots. Therefore, the stellar flares observed at all rotational phases could be resulting from a mixture of spotted and non-spotted regions resulting in no correlation between rotational phase and flare number. Alongside this, the larger energy flares are more present when there is spot activity present on the disc. This is particularly clear in the star HD 39150 in Fig. 7 where emerging spot and plage regions cause increased flaring activity as a result of shearing between varying magnetic polarities.

All of the discussions so far centre around the relationship between solar flares and sunspots on a cycle basis. The TESS observations are far too short to investigate cycle periods on our sample, even the ones observed in all sectors. It will take a few years for TESS to build up longer term observations of stars as it returns to sectors. Therefore, can we correlate the solar flare numbers within an activity cycle to the solar rotation period? The above work regarding solar flares discusses X-ray data while with TESS we deal with flare observations in the optical. What is required for the Sun is a discussion on whether there is a relationship between solar flares and sunspots on the rotational period basis. Unfortunately, catalogues of solar white light flares (WLFs) are very much incomplete: for example Matthews et al. (2003) list 28 flares over a 1-yr period detected with Yohkoh, a Japanese Solar mission. The catalogue from Kuhar et al. (2016) contains 43 M and X class flares which occurred from 2011 to 2015 and were observed by both SDO/HMI and RHESSI and Namekata et al. (2017) expanded on this adding another 11 observed in 2015. Overall, this data is not sufficient for a proper analysis of the above question. Moreover, obtaining the rotation period of the Sun as an effective light curve in time is a difficult process and despite irradiance measurements of the solar disc being taken, this is not something which is well studied in solar physics.

9 DISCUSSION

In Papers I and II, we find no evidence for a correlation between rotational phase and flare number within a sample of 183 M dwarf flare stars. We now have a similar study for a sample of 209 solar-type (F7–K2) stars observed in 2-min cadence by TESS in sectors 1–13. We determined rotation periods using an LS periodogram, identified and characterized 1980 flares within our sample and determined their energies between $10^{31}$ and $10^{36} \text{ erg}$. Similar to Papers I and II, we find no evidence of any correlation between rotational phase and flare number, indicating the flares are randomly distributed and do not occur alongside, the dominant star spot that is responsible for the rotational modulation. However, it was noted that increased levels of activity were observed in the star HD 39150 (TIC 364588501) when evidence of emerging star spot and plage regions were observed in the rotational modulation of the light curve. This finding does then suggest there is a relationship between flares and

| Flare classification | Energy range (erg) |
|----------------------|-------------------|
| X10                  | $>10^{32}$        |
| X                    | $10^{31}–10^{32}$ |
| M                    | $10^{30}–10^{31}$ |
| C                    | $10^{29}–10^{30}$ |
| B                    | $10^{28}–10^{29}$ |
| A                    | $<10^{28}$        |
star spots and agrees with the mechanism for flare generation as discussed by Chandra et al. (2010).

In Papers I and II, we identify four possible scenarios to explain the lack of a correlation including star–planet interactions, binarity, polar spots, and multiple spot locations. Here, we discuss these further while also bringing in other possible explanations. First, there is the potential for star–planet interactions (SPI’s) and interactions between two stars within a binary system. Only one of the solar-type stars in our sample, HD 44627 (TIC 260351540), has a known exoplanet. In this instance, the planet is orbiting at a distance (a = 275 au) which is unlikely to cause any SPI’s with its host star. However, this does not rule out any of the other stars in our sample having undiscovered exoplanets that could cause SPI’s.

Additionally, the stars in our sample could be in binary systems that could cause induced magnetic activity producing flares. Within our sample there are three stars whose TESS light curves show they are eclipsing binaries. These solar-type stars are CD-78 516, AF Cru, and HD 120395 (TIC 357911163, $P_{\text{orb}} = 1.63$ d; TIC 309528896, $P_{\text{orb}} = 1.89$ d; and TIC 243662768 $P_{\text{orb}} = 1.64$ d, respectively), which have rotation periods between 7.5 and 10 d, a spread in spectral types and show little flaring activity. The lack of flaring activity in these stars indicates that the period is long enough that interactions between the stars do not give rise to increased flaring activity.

Secondly, with our M dwarf samples in Papers I and II we discuss the potential for solar spots which could cause flaring activity at all phases if in the line of sight. It is important to note here that after spectral type M4 ($\sim$0.3 M$_{\odot}$) these stars become fully convective and so do not possess a tachocline, therefore, generating their magnetic field through a different dynamo mechanism in comparison to the Sun. However, polar spots or spots with high latitudes have never been observed on the Sun, therefore, you would assume polar spots are not possible on other solar-like stars. However, in a study by Schrijver et al. (2001) they simulate that solar spots could be possible on sun-like stars where a strong polar cap field leads to suppression of convection and formation of star spots and high latitudes. As a result, there is the possibility of polar spots being present on these solar-type stars which could be interacting with active regions at lower latitudes to produce flaring activity. Solar Orbiter (Müller et al. 2013), an ESA mission launched in 2020 February, will take high-resolution images of the Sun’s poles for the first time which will provide insights into the magnetic structure in more detail.

This then brings us on to the theory of multiple spot locations. During solar maximum, the Sun can be observed to possess many active regions that host spots including multiple spots at one location. As a result, it is entirely possible for our solar-type stars to possess multiple spot locations which could produce flaring at all rotational phases. Evidence of multiple spots was observed in the 1 yr light curve of HD 39150 (TIC 364588501) which was observed in the continuous viewing zone. In the TESS light curve of this particular star, the shape of the rotational modulation is observed to change over time with the whole light curve being fold-able on one rotation period and phase zero. This suggests multiple spots that are slightly out of synchronization producing the changes in the shape of the rotational modulation. As a result, we observe increased levels of flaring activity that co-align with the changes in the rotational modulation suggesting emergence of new spot regions and plage regions which interact with each other to produce the increased flaring activity. The large spot coverage of this and other G stars suggest youth. This is consistent with a study of the solar spectral irradiance variability over the last 4 billion years (Shapiro et al. 2020). The Total Solar Irradiance (TSI) variability of the young 600 Myr old Sun was about 10 times larger than that of the present Sun with its variability been spot-dominated, while by 2.8 Gyr its’ variability is faculae dominated.

As the relationship between solar flares and sunspots is well-established we used historic X-ray GOES flare data and SIlSO sunspot data to investigate this relationship further. We find sunspot and flare number are closely linked across the solar cycles where sunspot numbers increase as the Sun approaches solar maximum, so does the flare activity increase. Similar to Gao & Zhong (2016), we also discover the lower energy A and B class flares are anticorrelated with the higher energy X, M, and C class. This is interesting as the lower energy solar flares are more prominent during solar minimum when the sunspot numbers are low. As a result, this suggests these solar flares could be originating from plage or local dynamo regions and are not associated or correlated with sunspots.

This leads us on to our earlier finding of star spots and stellar flares not being correlated on our sample of solar-type stars. The anticorrelation between high- and low-energy solar flares and the lack of correlations between low-energy flares and sun spots could aid in understanding our lack of a spot/flare connections in our solar-type stars. There is the potential for the lower energy flares, which are observed to occur at all rotational phases, to result from plage regions or local dynamo regions as well. However, this does not explain our lack of a correlations between higher energy flares and star spots as they should occur together much like what is observed on a cycle by cycle basis on the Sun.

An alternative idea is that we should not attempt to correlate flare activity with spot number as this is not the main driver of magnetic activity. In a series of papers by McIntosh et al. (2014), McIntosh & Leamon (2014), and more recently Srivastava et al. (2018; and references therein Dikpati et al. 2019); these authors suggested that activity bands belonging to the 22-yr magnetic activity cycle is the main driver of solar activity, with these bands interacting at the equator. The idea behind this is an ‘Extended Solar Cycle’ that appeared to extend the activity butterfly back in time, about 11 yr before the formation of the sunspot pattern. Furthermore, these activity bands extend to much higher solar latitudes and would require a polar dynamo that is not a widely accepted idea. The observational evidence for the extended solar cycle is based on the evolution of coronal bright points, although the origin of this work dates back several years to Wilson et al. (1988). As noted by the authors, many large solar flares do not occur at sunspot maxima (e.g. see Odenwald, Green & Taylor 2006). They suggest that the longer these activity bands spent at very low latitudes, the higher the probability for large flares due to the formation of complex active regions.

With faster rotators, one may have several of these activity bands, thus a series of complex active regions producing super flares. The flare model proposed by Aulanier et al. (2013) fails to provide sufficient energy, to explain flares on M dwarfs, e.g. if we consider a typical M3–M4 dwarf that has a radius of about 0.3R$_{\odot}$ and a field strength of 2–4 kG. From their fig. 2, these values would reproduce a flare of $10^{34}$ erg; however, this would require a spot to cover nearly half of the visible stellar disc and still would not be able to account for the very large flare energies on some M dwarfs. In the case of solar-type stars, Aulanier et al. (2013) determine that a bipole coverage of 100 Mm and a field strength of 4 kG would be the conditions required to produce a flare of energy $10^{34}$ erg. They conclude solar-type stars that produce superflares must have stronger dynamo mechanisms than the Sun.
This then poses the question: Would the Sun be able to produce superflares with energies > $10^{33}$ erg? In Shibata et al. (2013) they investigate this question using current ideas related to the mechanisms of the solar dynamo. In their calculations, the Sun would need to generate a sunspot with magnetic flux of $2 \times 10^{23}$ Mx to produce a $10^{35}$ erg flare. In order to do this it would take the Sun 40 yr to store this magnetic flux and at present there is no known physical mechanism to make this possible. Overall, they conclude it is premature to say whether a $10^{35}$ erg flare would even be possible on the Sun given the current dynamo theories.

10 CONCLUSIONS

We have conducted an analysis into the statistics of superflares on a sample of 209 solar-type stars. Utilizing 2-min cadence data from TESS, we derived rotation periods for our sample and characterized 1980 flares. Two of our targets were observed in the continuous viewing zone so, with 1 yr of observations we carried out a short study into the variability of these stars. Our findings showed evidence of spot emergence, plage regions, and migrating spots which were connected to increased levels of flaring activity. Overall, we focused on the relationship between rotational phase and flare number finding no correlation between the two. We included an analysis on historic solar flare and sunspot data to investigate the relationship between flares and spots on the Sun, using our results to aid in understanding the lack of a correlation in our solar-type star sample.

By 2020 June, TESS will finish observing the Northern hemisphere and will return to sectors in the southern sky. Further observations of these stars will allow for follow-up studies, investigating their changing behaviour a year later. This will provide insights into the extended magnetic activity of these stars while also allowing for the search of activity cycles. Overall, the continued study of flares and star spots can aid in understanding the dynamo mechanism of other stars and how it relates to the Sun. All of this is extremely important when considering potential habitable systems that may orbit these active host stars.

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SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

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