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Monitoring the M-dwarf Host Stars of TESS Exoplanet Candidates: Stellar Flares and Habitability

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Monitoring the M-dwarf Host Stars of TESS Exoplanet Candidates: Stellar Flares and Habitability

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Abstract

In the search for life beyond our solar system, the study of M-dwarfs has become increasingly important due to their unique characteristics including their small size, flaring capabilities, and long lifespans. Their small size allows for exoplanet detection due to observable gravitational interactions, and the stellar flares could potentially trigger prebiotic life on exoplanets in the system. Lastly, their long lifespans may provide the conditions necessary to foster prebiotic life and the development of more complex organisms over time. Flare rate is a critical factor in determining the habitability of the exoplanet due to its potential to damage or incubate the surfaces of the exoplanets near the M-dwarf stars. This project aims to characterize the stellar flare conditions of a certain subset of M dwarfs which can then be used to determine the star's potential impact on any companion exoplanets in the system. Each of the candidates has been studied by the Transiting Exoplanet Survey Satellite (TESS) which provided the photometric data for this analysis. The 10 TESS candidates were selected using the Earth Similarity Confidence Metric (ESCM) as proposed by Bonney et al. (2019). The candidate stars in this list are the host stars of system with a potential planet in orbit that appears to be similar to Earth. By utilizing this prioritized list of promising candidates, the direction of future research on M-dwarf systems can be done in a more strategic and efficient manner to aid in the identification of an Earth-like, habitable exoplanet more quickly. The primary Python package used to obtain the data is *Lightkurve* while the primary modeling uses *emcee*. This paper presents a complete analysis of a confirmed flare found on the star found in the system TIC 29962054. These findings will greatly add to the body of knowledge of flaring behaviors of M-dwarf stars which will, in turn, aid to discover life beyond our Solar System.

Keywords: M dwarfs, flares, light curves, activity, habitability, TESS Survey

Chapter One: Introduction and Background Information

One of the most prominent reasons for studying the vast expanse of space is to discover life, especially on exoplanets that resemble the Earth. While the goal of this mission can be simply stated, the work that it entails is anything but simple. Because this is a complex undertaking, the task has been broken down into many parts with smaller objectives with specific criteria. The work done in this project aims to help answer a small part of that greater puzzle. The goal of this project is to look at the stellar flaring behaviors of several star-planet systems outside of our solar system that contain Earth-like exoplanets. The scope of this project was further constrained to systems that have M dwarf host stars due to their abundance and specific properties that make these stars useful. The following sections will orient how this project fits into the overarching quest of searching for life.

I. M dwarf Star Classification
II. Stellar Flares
III. Satellite Missions and Sky Surveys
IV. Habitability Criteria

I. M dwarf Star Classification

According to Henry et al. (2006), "M dwarf stars are the most abundant class of stars, as it is estimated that they constitute more than 70% of the stars in our solar neighborhood." Due to their sheer abundance, these stars are a natural place to begin studying exoplanet systems. Studies such as this one can aid in optimizing and improving observational techniques and our overall understanding of exoplanet systems which can be translated to observing larger systems on the scale of our home Solar System. M dwarf stars, also commonly called Red Dwarfs, have a spectral type that is dominated by a strong titanium oxide absorption band which places these stars in the red end of optical light (Dieterich, 2020). M dwarf stars exist on the coolest edge of the main sequence and have masses that range from $\sim 0.10 - 0.60\, M_{\odot}$ with low-surface temperatures, $T_{eff} \simeq 2{,}500 - 4{,}000\, K$, contained within a small diameter that is generally a few tenths of the Sun's diameter (Rodriguez-Lopez, 2019; Graham, 2022). M dwarf stars are completely convective which means that "the energy and material generated by fusion in the stellar core [are] carried up to the surface of the star, where it cools and sinks back down to be heated again," (Graham, 2022). This constant mixing means that the star survives until the hydrogen supply is depleted and the star collapses. With the combination of the star's low temperature, small size, and efficient hydrogen fusion, these stars exist on large timescales which is the main reason behind their abundance (Billings, 2015).

M-dwarfs have come to the forefront of current exoplanet research due to their abundance as well as their unique characteristics that may allow these stars to play a role in triggering and fostering prebiotic life on companion exoplanets. Due to their relatively small size, M-dwarfs are exceptional at aiding in the detection of nearby exoplanets due to the gravitational interactions of the stars and the planets. Since M dwarf stars are relatively small, exoplanets must orbit at smaller radii than planets in systems with larger stars such as the Sun in our Solar System. In M dwarf systems the stars and exoplanets are more comparable in size and mass which leads to a noticeable "wobble" effect on the stars in a periodic motion repeating every few weeks or months (Billings, 2015). This provides an observable way to detect the presence of exoplanets near the M-dwarf star that cannot be done with systems involving larger stars. Each of the stars that were studied in this paper fall under the M dwarf classification as opposed to our Sun which is classified as a yellow dwarf.

II. Stellar Flares

Stars have complex magnetic fields and there are many phenomena that can be observed when these field lines get tangled or snap. One such event is called a Stellar Flare which occurs when there is a sudden burst of magnetic energy and electromagnetic radiation that can be observed in many wavelengths of the Electromagnetic spectrum from radio waves to gamma rays (Oliver, A.C., 2021). These are "explosive magnetic reconnection events that occur within the star's magnetosphere," (Gunther et al., 2019). Flares can last anywhere from a few minutes to a few hours and can emit energy ranging from $10^{23}\ ergs$ for a nanoflare to $10^{33-38}\ ergs$ for superflare events. (Gunther et al., 2019). Additionally, flares can be accompanied by a coronal mass ejection (CME) which refers to when a cloud of charged particles is ejected from a star in a particular direction (Gunther et al., 2019).

Since M dwarf stars are fully convective, M dwarf stars can essentially flare continuously unlike our Sun in which powerful flares are uncommon. Except in the case of a supernovae event, stellar flares are generally the main cause for the movement and expulsion of hot material and high energy emissions within stars (Basri, 2019). These stellar flares follow a cumulative energy distribution that follows a general power law relationship (Van Doorsselaere et al., 2017). This means that the stronger a flare is the less likely it is to occur. Additionally, when considering the inferred geometry of the stellar flares from M dwarf stars, it is supposed that the active flaring region of a star can extend up to a stellar radius in dimension from the star's surface (Basri, 2019). Though not all M dwarf stars produce powerful flares every day, it is critical to consider the flaring behavior of any star that may host Earth-like planets as it can have a great impact on the potential habitability and evolution of those planets. Stellar flares could erode atmospheres, compromise ozone layers and create harsh conditions for life on nearby planet surfaces (Gunther et al., 2019). Since flares can play an integral role in the habitability of nearby planets, it is critical that their flaring behavior is studied and characterized.

III. Observations and Satellite Missions

The primary source of the data analyzed here came from the Transiting Exoplanet Survey Satellite (TESS) which is an MIT-led NASA-funded mission that launched in April 2018. A particular aim of this mission is to find a multitude of planets outside our solar system that are Earth-sized and orbit bright stars that may have the potential to harbor life (Gunther et al., 2019). TESS makes it possible to "study flares on early to late M dwarfs," especially on bright stars in our solar neighborhood (Gunther et al., 2019).

Over the two years of its primary mission, the four cameras aboard TESS will take a comprehensive survey of the entire sky which has been broken down into 26 sectors and will measure the light curves of over 200,000 stars over the course of approximately 27 days (Garner, 2016). The wavelengths that TESS is sensitive to range from visible blue at 600nm to near infrared at 1000nm (Guerrero, 2021). The light curves that result from this study will provide great information into the behaviors of these stars, especially in terms of stellar flares. The promising candidates that TESS flags create a comprehensive catalog of targets for researchers to study further and analyze (Garner, 2016). Each of the candidates studied in this paper was initially flagged by TESS and then determined to have an Earth-like planet within its system.

IV. Habitability Criteria

The idea of searching for life beyond Earth is a broad undertaking that often involves looking for signs of life (either present or past) rather than hoping to find complex organisms first. These signs of life are based on our current understanding of the requirements of life on Earth. Because of this, the search for life beyond Earth has been narrowed to looking for Earth-like worlds with the resources to harbor microbes as found on Earth (Bonney et al., 2019; Fraknoi et al., 2016). Since water is essential to life as we know it, the first criteria a planet must meet is to be within the host star's habitable zone. This zone refers to the range of distances from the host star that could sustain liquid water on its surface. If a planet is within this zone, it is a good sign but far from definitive proof of life.

Some potential threats to the habitability of planets near M dwarfs are tidal locking and stellar flares. If tidal forces cause one hemisphere of the planet to always to face the star, which is the case if the orbital period syncs up with the rotational period, then this could pose a potential threat to the habitability of that planet's surface (Billings, 2015). In the most extreme scenario, the planet's air and water could freeze and accumulate as ice on the cold nightside, while the illuminated side could be scorched by impending flares rendering the planet uninhabitable (Billings, 2015). In the case of stellar flares, an equally devastative effect could occur. Since M dwarf stars are more prone to flaring and have exoplanets in relative proximity, the exoplanets could be unpredictably bombarded with x-ray and UV radiation which could make it difficult for a stable climate and healthy biosphere to occur (Billings, 2015). This sentiment is further noted by Gunther (2019) who warns that stellar "flares may erode exoplanets' atmospheres and impact their habitability but might also trigger the genesis of life around small stars." In this more positive case, whatever the fate of these exoplanets may be it is critical to understand the flaring capabilities of these stars in order to understand the evolution and habitability of these planets and their atmospheres (Gunther et al., 2019).

Before any definitive determinations about the habitability of these exoplanet systems, the M dwarf host stars must be understood in detail. There has been much previous work done to determine and model these stars' masses, distances, compositions, and Mass-Luminosity relations (Dieterich, 2020), though there is still much more work to be done in order to make any definitive claims. The candidate stars selected to be studied in this investigation have shown to have Earth-like exoplanets within their systems which means that further understanding of the flaring dynamics of these systems will greatly aid in providing more evidence for potential habitability.

Chapter Two: Methodology

I. TESS Candidate Selection with the Earth Similarity Confidence Metric

The TESS Mission found thousands of potential exoplanet candidates that need to be studied further. However as Bonney et al. (2019) points out, "as more planet candidates are detected and confirmed, it becomes increasingly important to strategically search for the signs of habitability with which to differentiate and prioritize the candidates." Within that paper, the planets were prioritized based on how similar they were to Earth. More explicitly, the Earth Similarity Index (ESI) (Schulze-Makuch et al., 2011) was calculated for each of the candidates and they were then prioritized based on the Earth Similarity Confidence Metric (ESCM) as proposed in Bonney et al., 2019. Thus, by utilizing these carefully selected candidates, our research will be more strategic by choosing to characterize the M-dwarf stars that not only have the theoretical ability to trigger prebiotic life on companion exoplanets due to their flare activity but that the exoplanets in question are similar to Earth. The top ten candidates based on this metric are listed in (Table 1) and they represent the most Earth-like of the sample. The TIC ID refers to the number assigned to the object in the TESS Input Catalog (TIC). The TESS TOI refers to what is called a TESS Object of Interest (TOI).

Table 1: Promising Candidates for Observations from Bonney et al. 2019 to be analyzed in this study.

Prioritized TESS Planet Candidates by Earth Similarity Confidence Metric (Bonney et al., 2019)					
TESS OI#	**TIC ID**	**2MASS designation**	**TESS Follow-up Disposition**	**TESS Magnitude**	**Potential Number of Planets in System**
TOI 198	TIC 12421862	2MASS J00090428-2707196\	Planetary Candidate	9.92801	1
TOI 1266	TIC 467179528	2MASS J13115955+6550017\	Planetary Candidate	11.0402	2
TOI 732	TIC 36724087	2MASS J10183516-1142599\	Confirmed Planet	10.5848	2

TOI 406	TIC 153065527	2MASS J03170297-4214323\	Planetary Candidate	11.2828	2
TOI 256	TIC 92226327	2MASS J00445930-1516166\	Known Planet	11.2991	2
TOI 698	TIC 141527579	2MASS J05505661-7637132\	Planetary Candidate	12.1293	1
TOI 1633	TIC 165551882	2MASS J17470388+5713288\	False Alarm	12.5441	1
TOI 782	TIC 429358906	2MASS J12154108-1854365\	Planetary Candidate	12.2875	1
TOI 203	TIC 259962054	2MASS J02520450-6741155\	False Alarm	12.2423	1
TOI 237	TIC 305048087	2MASS J23325824-2924540\	Confirmed Planet	13.1402	1

Since this list of candidates was made in 2019, two candidates have been determined by follow-up studies to not be planets, but rather false alarms. These candidates are TOI 1633 and TOI 203 as indicated in Table 1. The flaring characteristics can still be studied in these stars, but the results could not be extended to potential habitability conditions as there are no planets confirmed to be orbiting the star.

II. TESS Data Specifics

The main data that were downloaded for analysis for this project from TESS Data Releases were Target Pixel Files (TPFs) and Lightcurves. As TESS observes the changes in brightness of a star on a large timescale of 27 days. The time that is reported for these observations is by default given in TESS Barycentric Julian Day (BTJD) which is "Julian day minus 2457000.0 and corrected to the arrival times at the barycenter of the Solar System," (TESS, 2018). The same object can be studied in multiple sectors which means that for each of the candidates being studied, there could be multiple observations of the same star which increases the chances that major flaring activity (if present) should be recorded within the data. As TESS observes a particular target, a file is generated "containing the original CCD pixel observations," (TESS, 2018). Because of this, TPFs can be a great source of information about the flux of a star as well as a way to identify potential sources of noise or other systematic trends. These are the first data piece to be downloaded for each candidate using the *Lightkurve* Python package (Lightkurve Collaboration, 2018). TPFs are smaller sets of data in 2-minute cadences that are often easier to work with than the larger TESS observations that occur in 30-minute cadences. The light curves for each star can be extracted from the TPC which shows the changes in flux recorded for the star over time. The flux that is used to create these light curves has had the noisy, background flux removed to isolate the flux that is strictly coming from the star.

III. Methodology

In determining a method to systematically search for flares within the data for these candidates, the methods were loosely based on the methods used in the study done by Gunther et al (2019) which looked at flares present in almost 25,000 targets from the first TESS data release. In that study, the overall process was to download the data, flag flares with initial criteria, then use the *Allesfitter* code unique to Gunther et al. (2019) to model the flares using two Markov Chain Monte Carlo (MCMC Chains). Throughout that process, there were several errors-correcting measures to ensure the completeness of the flare detection and modeling pipeline.

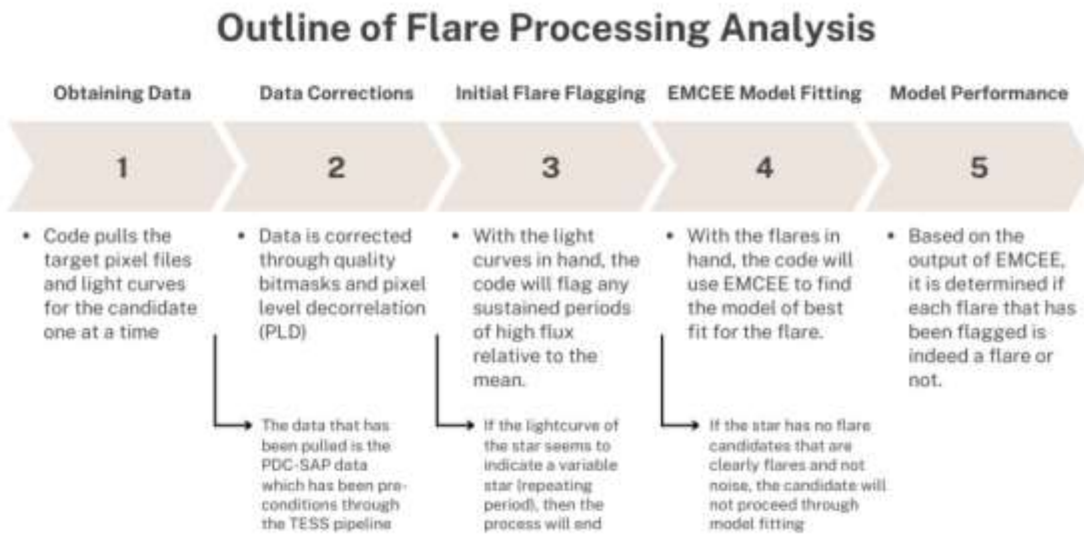


Figure 1: *Outline of Process Used in this Investigation to Analyze the Candidates for Flares*

The process used in this study is outlined in the flowchart shown in Figure 1. The process begins with downloading the Target Pixel Files and Light Curves of each candidate from the TESS data releases using *Lightkurve.* The data is then corrected through quality bitmasks and pixel-level decorrelation as well as flattening of the light curve before any analysis is performed. If a candidate is visually inspected and found to be a variable star with a repeating periodic pattern, then the object will not be studied further in this investigation. Variable stars do flare as other stars do, however, our modeling functions do not account for variability within these candidate stars, so they cannot be studied simply using the code since the code does not account for the regular variability present in those types of stars. Once the data has been conditioned and corrected, the initial, robust flare flagging can begin. This is the most simplistic way to search for flares and provides a basis for later modeling. There is a chance that there will be no flares flagged for these observations of these stars. If no flares are detected in the phase for a star at all, then it is preliminarily said to have low flaring activity and will not be analyzed further. If a candidate does have flares flagged in stage 3, then those flares will be modeled using the *emcee* Python package (Foreman-Mackey et al., 2013) which is an Affine Invariant Markov Chain Monte Carlo Ensemble sampler similar to the methods used by Gunther et al. (2019). The following sections break down this flare processing procedure even more.

IV. Systematic Data Corrections

a. Pipeline Corrections PDC SAP data

There have been some corrections made on the data in its pipeline before it was publicly released for our purposes. The flux data that was used is the PDCSAP Flux or Pre-search Data Conditions Simple Aperture Photometry. The SAP (Simple Aperture Photometry) flux corrects the values for instrumental variations and the PDCSAP flux uses that as a baseline to further ascertain the "mission's best estimate of the intrinsic variability of the target," (Fleming, 2018).

b. Quality bitmask

When downloading the data itself, it is also critical to specify the quality of data to be downloaded which is achieved by using Quality Bitmask. In the case of this project, the default quality bitmask was used to broadly identify and ignore all data points which are definitively useless (TESS, 2018).

c. Pixel Level Decorrelation (PLD)

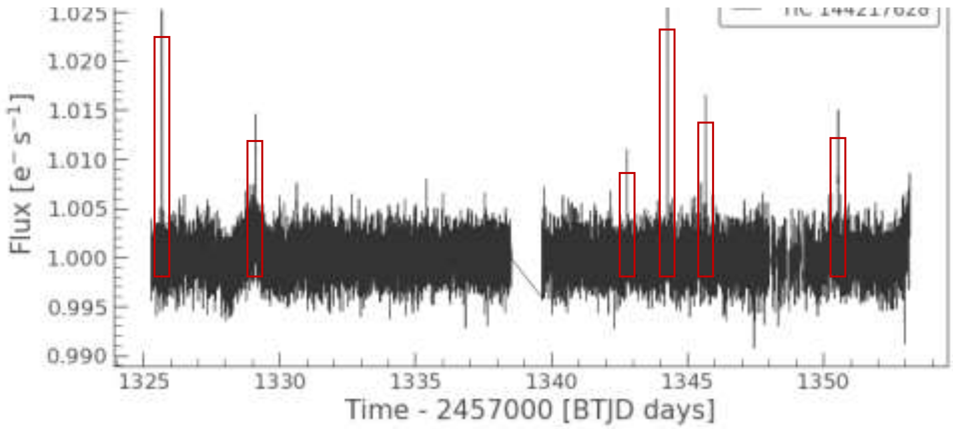
One of the major adjustments that were made to the dataset was the method of Pixel Level Decorrelation (PLD) which is a method through which systematic trends introduced by small spacecraft motions can be removed (Lightkurve Collaboration, 2018). This method will help to improve the precision of the data before any additional analysis is conducted.

In short, PLD corrects the dataset "by identifying a set of tends in the pixels surrounding the target star and performing linear regression to create a combination of these trends that effectively models the systematic noise introduced by spacecraft motion. This noise model is then subtracted from the uncorrected light curve," (Lightkurve Collaboration, 2018).

V. Initial Flare Flagging with Lightkurve

For this project, the criterion used to flag potential flares within the data was the same as the criterion used in Gunther et al. (2019). In the study done by Gunther et al. (2019) the flare candidates were required to have six minutes of continuous flux data that was above the 3σ threshold. This criterion was slightly modified in this analysis to allow for the characterization of smaller flares. Flare candidates in this study were required to have at least six minutes of continuous flux data above a 2.5σ threshold. The value for sigma was calculated by calculating the standard deviation of the flux data. As referenced by Gunther et al. (2019), "these criteria are empirically selected to separate noise and actual flaring objects. For example, when looking at the flattened light curve for candidate TIC 144217628 which is a candidate studied by Gunther et al. (2019). In this case, our code would have flagged the six major increases in flux as potential flares to be further analyzed for flares.

Figure 2: *Flattened Light Curve for TESS Candidate TIC 144217628 Studied by Gunther et al., 2019. Major flare candidates are flagged in red.*



VI. Modeling Flare and Fitting Data with EMCEE

The main purpose of using emcee is to fit a model to our data to further confirm that the splice of the light curve that has been flagged as a period of high flux actually fits the shape of a flare. In general, a flare will have a steep incline and decline as they are explosive events. This will be reflected in the shape of the model. This method is composed of three functions that work together to gather all the necessary inputs for the emcee method. The input theta is used in many of these functions and is comprised of our defined parameters. These parameters include the maximum flux of the flare, the time at which the maximum flux occurred, the full-width half-maximum, as well as 8 other parameters defined in Davenport et al. (2014). These parameters from Davenport et al. (2014) provide an empirical flare template that is used to aid in the fitting of the model to the data.

First and foremost, the log_prior method constrains the parameters only to include real and valid solutions. Priors are necessary in order to use MCMC methods because samples will be drawn from the probability function. Second, the log_likelihood function aims to numerically optimize Equation 1.1 below which is simply a Gaussian (Foreman-Mackey et al., 2013). This function will return the maximum likelihood result for the model.

$$\ln p(\,y|x,\sigma,max,fwhm,maxtime,a,b,c,d,e,f,g,h) = -\frac{1}{2}\sum_{n}\left[\frac{(y_{n-maxtime})^2}{\sigma_2}\right] + \log(2\pi\sigma_2) \quad (1.1)$$

where σ_2 is

$$\sigma_2 = yerror^2 + flare\ time^2 \quad (1.2)$$

Once the prior and likelihood functions have been defined, the full log_probability function can be defined. This probability function takes the priors and likelihoods into account and returns the probability. With all these functions defined, *emcee* begins by “initializing the walkers in a tiny Gaussian ball around the maximum likelihood result…and then run [7,000] steps of MCMC,” (Foreman-Mackey et al., 2013). In this case, 32 walkers were used. Once *emcee* has finished running, the model’s performance can be checked using two diagnostic plots: a corner plot and a projection of the model over the data. The corner plot is a quick way to show the covariances within the data as well as create a histogram of each parameter independently. It should be noted that this entire process will only be completed if a flare is indeed a flare.

Chapter Three: Results & Discussion

I. Complete Analysis of Flare from TIC 259962054

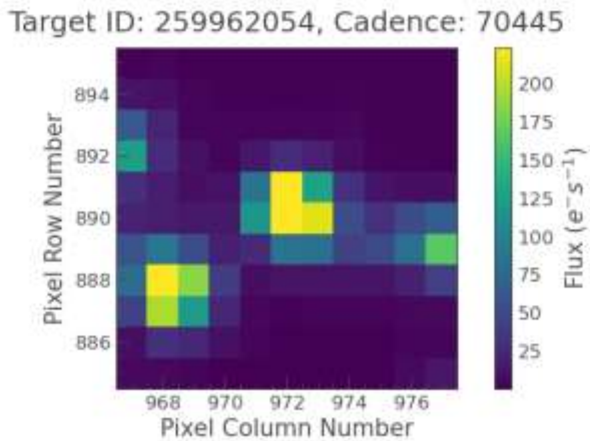
Since the list of targets used in this sample was very small (10), there is no guarantee that there will be good flare observations within this dataset. One of the first qualifying stellar flares comes from candidate TIC 259962054. I should note that this was, in fact, one of the candidates that did not have any confirmed planets orbiting it, however, that fact does not preclude it from flaring. Because of this, I will show the complete analysis of this flare to demonstrate how a good flare candidate can be studied if/when they are observed in systems that do have planets. This candidate yielded the best flaring candidates. Using the ExoFOP online database, the characteristics of this host star were gathered and listed in Table 2.

Table 2: *Characteristics of the Host Star of the TIC 259962054 System*

Characteristics of Host Star from TIC 259962054 System from ExoFOP	
Right Ascension and Declination	02:52:04.34; -67:41:13.26
Effective Temperature (T_{eff})	3203 K
Stellar Radius	0.241 $R_{\odot}$
TESS mag	12.2423
V mag	15.017 mag
Metallicity	-0.81
Stellar Mass	0.202161 $M_{\odot}$
Stellar Density	32.2 g/cm^3
Stellar Luminosity	0.00516 $L_{\odot}$

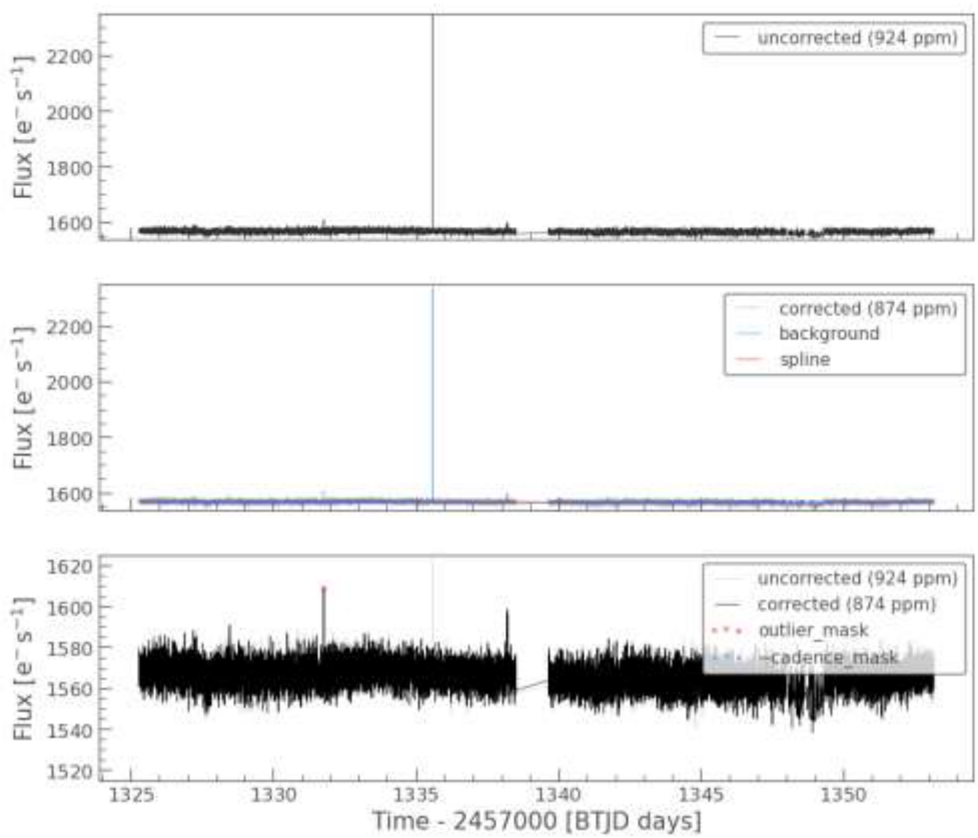
The first step of this process was to download the Target Pixel File (TPF) for this candidate at this particular cadence. The “postage stamp” TPF is shown below in Figure 2.

Figure 3: Target Pixel file for this Observation of TIC 25992054



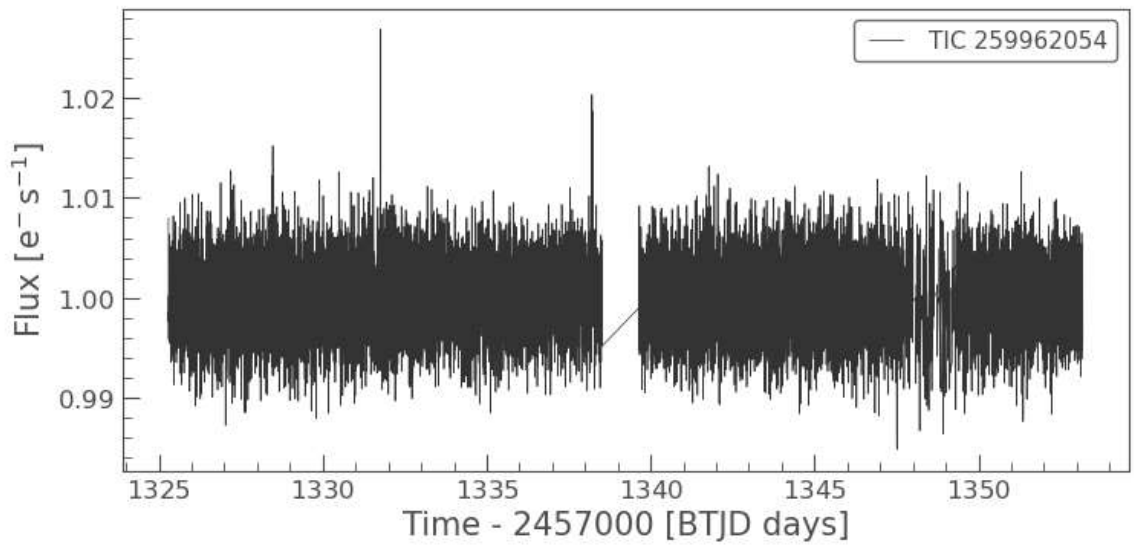
With the data in hand, the data is now corrected according to the Pixel Level Decorrelation method outlined previously. The effects of this data correction can be seen in Figure 4 below which directly contrasts the uncorrected and corrected data. The top plot shows the data as-is, the second plot shows the first step of correction using a spline, and the bottom plot shows the data after outliers have been removed. A clearer example of the benefits of Pixel Level Decorrelation on the bulk of the dataset will be shown in a later section.

Figure 4: Pixel Level Decorrelation Correction of TIC 2599054's Light curve



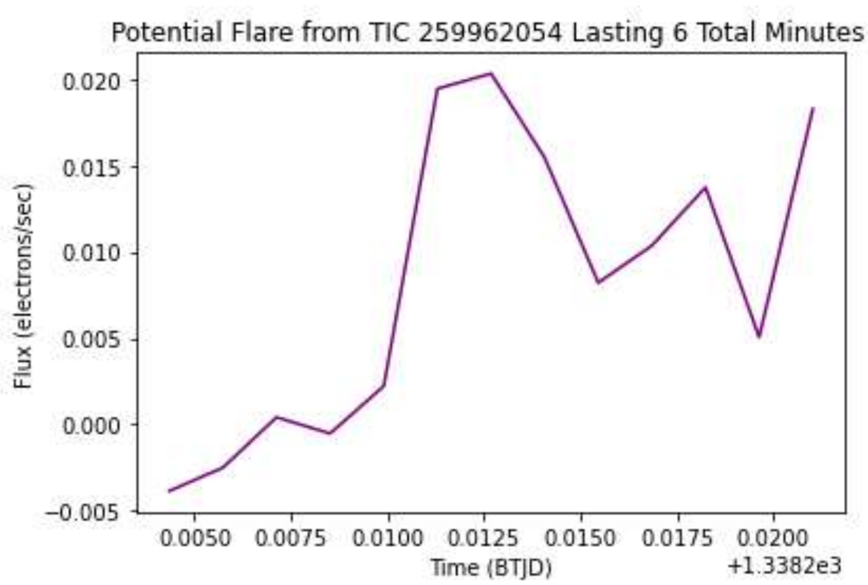
Due to the presence of a major outlier, this plot is rather skewed. After the removal of that outlier with earlier corrections and by flattening the light curve, the potentials flares become more apparent as larger spikes that stray from the baseline of the light curve. The flattened light curve for TIC 259962054 is shown below in Figure 5.

Figure 5*: Flattened Light Curve for TIC 259964054*



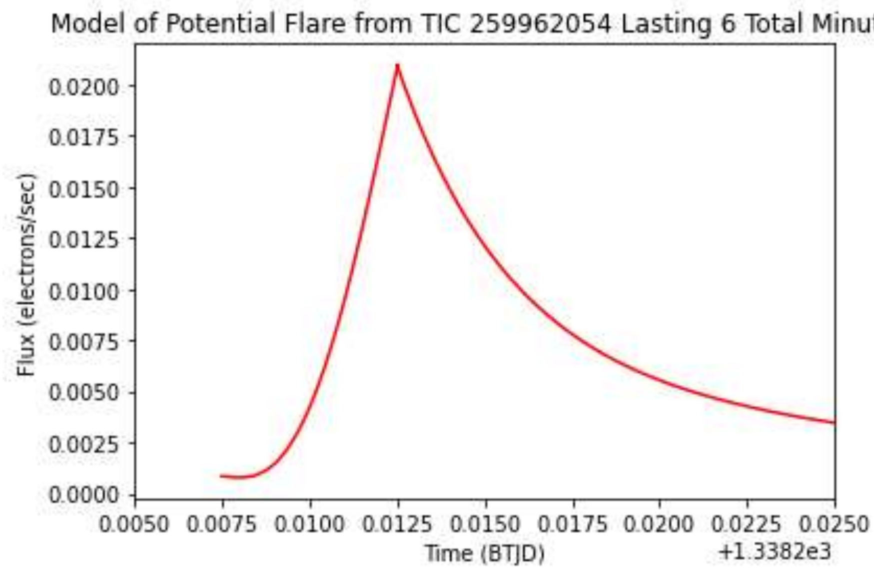
The code first checks robustly for flares that meet the criteria of being at least 3 standard deviations from the mean for at least three counts or six minutes. The standard deviation for the data of this flare is σ = 0.0035, so thus 3σ = 0.0106. This flare just barely met the criteria as it sustained increased flux levels above 3σ for exactly six minutes. The plot below shows the flare that was flagged here with a margin of a few counts on either side to provide context to the behavior.

Figure 6*: Initial Flare that was flagged and spliced from the original light curve.*



This flagged flare was then modeled using *emcee*. As noted earlier, the inputs to *emcee* are the dataset of time and flux around the flare, the full-width half max of the flare, the maximum peak of the flux of the flare, and the time of the maximum peak of the flare. The model additionally uses the 8 additional parameters from Davenport et al. (2014). Using these inputs, the *emcee* algorithm used 7000 walkers to create the model which is plotted below in Figure 7 with the same axes as the light curve.

Figure 7: *EMCEE Model of Flare 259962054*



Then, once the data and the model are plotted on the same axes, the model presents a good fit to the flare data providing further evidence that this is a flare. This is shown below in Figure 8.

The known characteristics of this flare based on this analysis is shown below in Table 3. These provided many of the inputs to the model fitting function.

Figure 8: *Model fit to Data for Flare Observed in TIC 259962054*

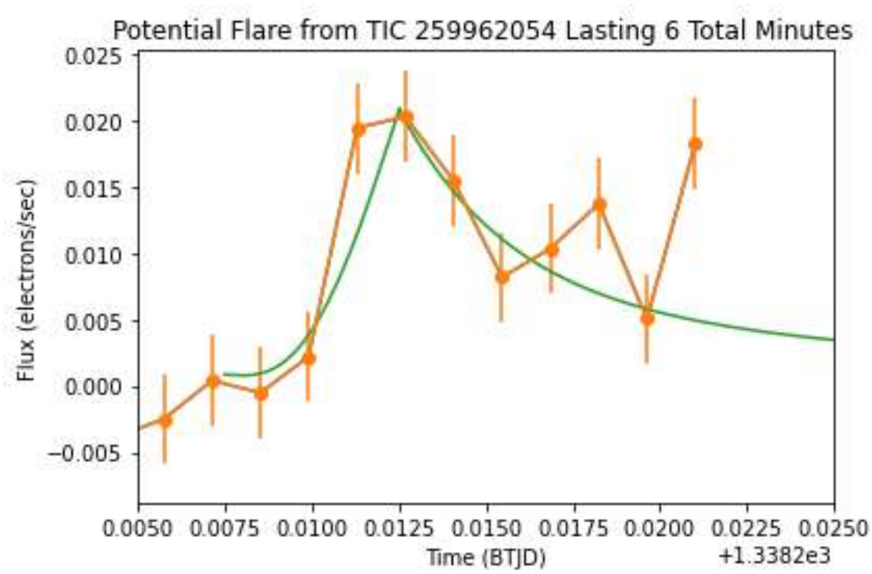


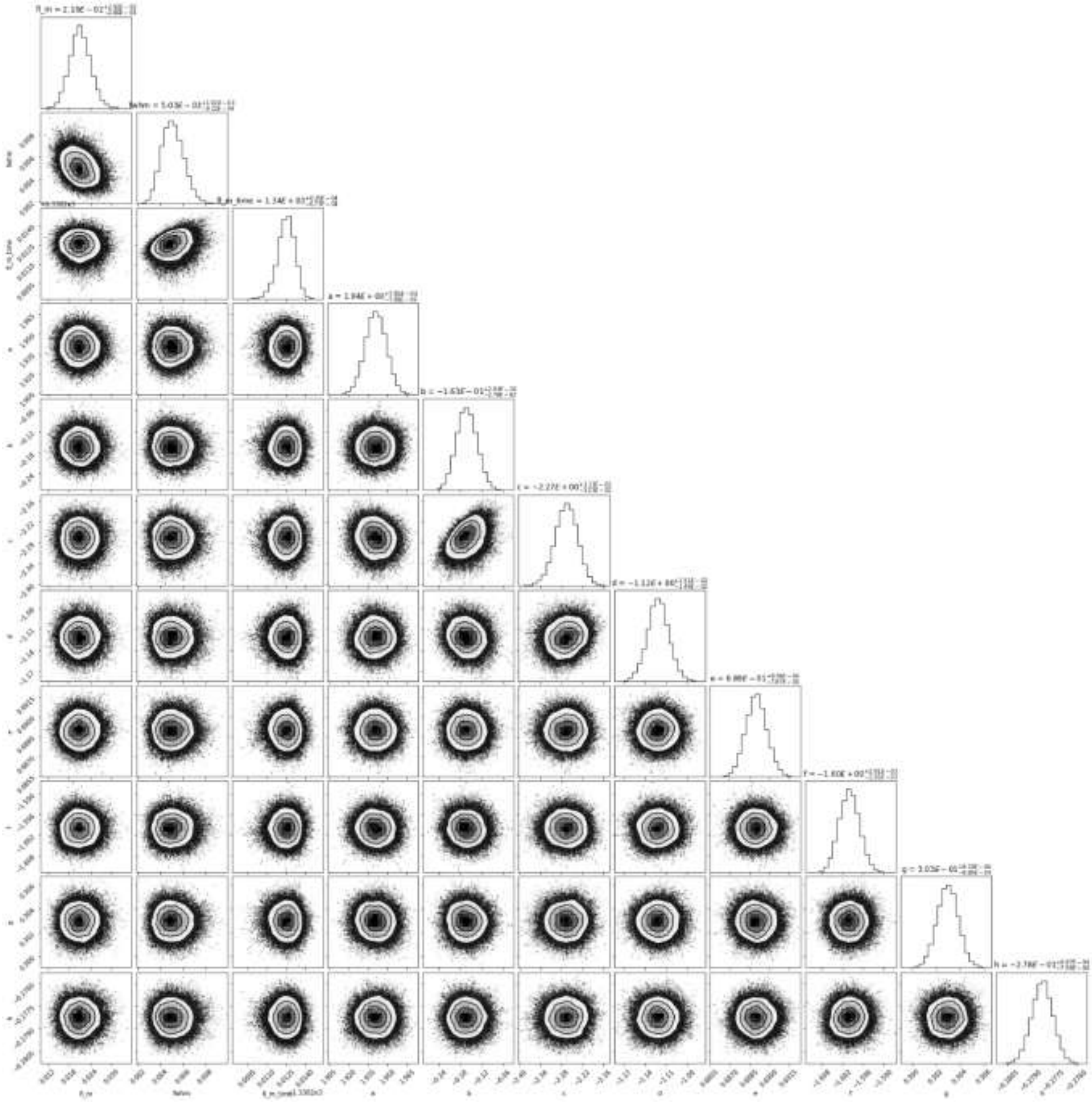
Table 3: *Characteristics of the Observed Flare from TIC 259962054*

Characteristics of Flare from TIC 259962054	
Flare Duration	6 Minutes (3 Consecutive 2 Minute Cadences)
Mean Flare Flux	1.5936e-05
Standard Deviation (σ)	0.00354571
Threshold (3σ)	0.01063712
Peak Flare Flux	0.02033200 $(\boldsymbol{Wm^{-2}})$
Peak Flare Time	1338.21 BTJD
Full-Width Half Maximum (FWHM)	0.0042517

When using MCMC analyses, it is critical to make a corner plot to ensure that there are no covariances within the data. The corner plot checks for covariances between many of the input variables such as the FWHM, peak flare flux, and peak flare time. There should be no covariances or linear correlations observed which is true for this corner plot which can be seen by circular correlations which are indicative of the two parameters not being correlated. The corner plot for this particular flare is shown below in Figure 9. Due to the complexity of this plot and the limited space in this publication, the full Figure 9 can be viewed using this link where zooming in is possible.

(https://drive.google.com/file/d/15BEewF4SYKRlFMt6-5quJ278SucUcoUy/view?usp=sharing)

Figure 9: *Corner Plot for the Flare Observed in TIC 259962054*



II. Complete Dataset Characteristics

The previous section detailed the analysis of a single flare found in one observation of a target from the candidate list. The purpose of this section is to give a clearer picture of the dataset as a whole. Table 4 below details the number of TESS observations that are available for each candidate, the number of flares flagged by the simple sigma level criterion, as well as the number of flares that can run through *emcee* successfully. The last crition is simple by visual inspection. A simple flare – which is all that this method can appropriately handle at the moment – is simply made up of a single sharp incline, reaching a peak, followed by a sharp decline. There are cases where flares can be flagged, but not resemble the shape of a flare. These potential flares that don't meet the criteria for a simple flare may be complex flares with multiple energy releases or they may not be flares at all. The robust splices of the light curve that indicate a possible simple flare were collected for each candidate and saved for future analysis. The rest of the flares that have been flagged through this process will be analyzed in a similar fashion to the complete flare analysis for the flare from TIC 259962054 above.

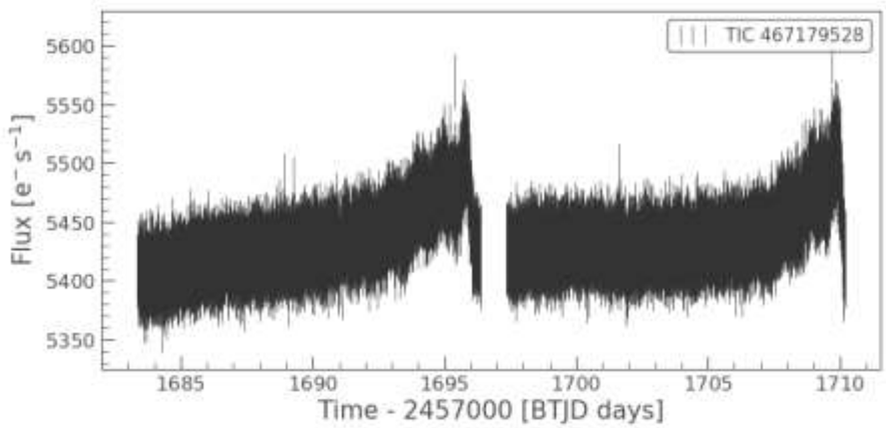
Table 4*: Number of Observations and Potential Flares for Each Candidate*

Potential Flaring Behavior for the Candidate List					
TIC ID	**Number of Observations Available at 2 Minute Cadences**	**Number of Flares Flagged by the Initial Sigma Method**	**Number of Potential Simple Flares**	**Average Mean Flux of Flagged Flares (Wm^{-2})**	**Stellar Luminosity ($L_{\odot}$)**
TIC 12421862	3	7	2	8.95199e-05	0.03688
TIC 467179528	6	1	0	N/A	0.02930
TIC 36724087	2	0	0	N/A	0.01553
TIC 153065527	4	7	3	0.0001154	0.01660
TIC 92226327	2	9	3	0.0001298	0.00421
TIC 141527579	27	15	7	0.0001529	0.03100
TIC 165551882	16	0	0	N/A	0.01301
TIC 429358906	2	0	0	N/A	0.01809
TIC 259962054	7	16	10	0.0003961	0.00516
TIC 305048087	2	1	1	0.007084	0.00427

III. Variable Star Caveat

As previously mentioned, this analysis is no equipped to handle flares on variable stars. The light curve of a variable star may look like Figure 10 below which shows TIC 467179528 has two repeating curves rather than the almost randomized light curves seen in TIC 259962054 below.

Figure 10: *Light Curve of TIC 467179528*



Chapter 5: Conclusions and Future Work

This study has demonstrated the effectiveness and feasibility of using robust and Markov-Chain Monte Carlo analysis methods to determine the existence of stellar flares on M dwarf stars. In the flare that was fully characterized for TIC 259962054, the flare sustained a level of flux above three standard deviations for six minutes. The peak flux of this flare reached a level of 0.02033 electrons/second which occurred at the time 1338.2119 BTJD. The potential flare candidates are reported for each one of the candidates which can be used for further flare analysis in future studies. The work done in this project is simply the first step forward in characterizing the flaring behavior of a select few stellar candidates that have Earth-like exoplanets. The more the flaring behavior of these host stars can be characterized and understood, the more the effects of these flares on nearby, Earth-like exoplanets can be understood. These flares have the potential to destroy any hope of life on the planets or even trigger and incubate life as Gunther et al (2019) mention. This delicate balance is precisely the reason why stellar flares play an integral role in the search for life especially around M dwarf stars.

In the future, I hope to characterize these flares more fully for each candidate while also refining the analysis methods to increase the confidence in the results in a multitude of scenarios beyond just simple flares. Additionally, the more accurate information about the flaring rate and environment of these stars will be of great aid as researchers develop models of the atmospheres of these extrasolar planets. The more information that can be gathered on these stars can help to prioritize telescope observations in a more efficient manner.

Chapter 6: Effective Education on Flaring Tendencies of TESS Exoplanet Candidates

At its core, scientific research aims to expand the boundaries of human knowledge through its investigations of the natural world. In order to make scientific progress, collaboration and communication within the scientific community as well as the public at large are necessary. In an effort to allow this thesis to represent not only my technical research but also my secondary goals which focus on education outreach and effective communication, this section will outline how this information can be communicated to a certain subset of the population, namely students. By taking a survey of the current astronomy curriculum both national and state standards[1] as well as gathering input from in-service educators and educational professionals, this paper will make recommendations about how this topic can be broached with students as well as provide a current selection of freely available resources for teachers to use.

I. Research Question
II. Current Curriculum
III. Survey of Inservice Teachers and Educational Professionals
IV. Recommended Selection of Resources
V. Conclusions

I. Research Question

The purpose of this portion of the project is to detail how the teaching of this topic could fit within the framework of the current curriculum that must be followed in high schools while also providing links and justification to several current resources. Oftentimes well-intentioned scientists and institutions, aim to produce lessons and resources to aid teachers in teaching astronomy. While this is a necessary and worthwhile endeavor, these resources do not always readily align with the curriculum and thus make it hard for teachers to easily incorporate them into their lessons. Additionally, the constraint of time is very present within schools as there is often more material to cover than there is class time. Because of this, teachers may not use resources or teach topics that stray from the standards to delve too deep for the grade level. Taking all of these constraints into account, this section aims to show how the topic of stellar flares covered in this paper can fit into the current curriculum frameworks, gather advice from in-service teachers and educational professionals to ascertain what resources would be most handy, and finally present a cultivated list of resources that can be used by teachers to present the topic of stellar flares and solar activity to their students.

II. Current Curriculum

To better understand what resources may be most valuable to current teachers, I wanted to survey current curriculum sources across the United States to gauge the depth

[1] In this paper, the Arkansas Statewide astronomy standards were used. These specifications may change from state to state, so please also consult any local curriculum.

and breadth that they cover. Starting locally, the first source I reviewed was the Astronomy Standards from the Arkansas Science Standards which covers the instruction of students from kindergarten through high school. According to this curriculum structure, the topic of the project falls under Topic 7 which covers Stellar Evolution. The excerpts below

Table 5: Arkansas State Astronomy Standards Excerpts (Arkansas Department of Education, 2016)	
Central Questions	Expectations on this topic are to help students understand the following: • "How does a star's initial mass and composition uniquely determine its stability, lifespan, structure, and final state after cataclysmic star death?" • "Where do various elements in the universe originate and what processes account for their production and abundance?"
Student Performance Expectations	Students who demonstrate understanding can: • "Develop a model based on evidence to illustrate the lifespan of the sun and the role of nuclear fusion in the sun's core to release energy in the form of radiation. [AR Clarification Statement: Emphasis is on developing a model based on evidence to illustrate the lifespan of the sun.]" **A7-ESS1-1** • "Communicate scientific ideas about the way stars, over their lifecycle, produce elements. [AR Clarification Statement: Emphasis on the fusion process and the production of elements of atomic #2 (helium) - #26 (iron); elements more massive than iron are produced only during a supernova event at the end of a star's life.]" **A-ESS1-3** • "Construct an explanation of how a star's initial mass uniquely determines the conditions that affect stability and factors that control the rates of change over its lifetime. [AR Clarification Statement: Emphasis is on how initial mass determines the life cycle of a star as described by the Russel-Vogt Theroem.]" **A-ESS1-1AR**
Disciplinary Core Ideas	PS4.B Electromagnetic Radiation • "Atoms of each element emit and absorb characteristic frequencies of light. These characteristics allow identification of the presence of an element, even in microscopic quantities. (A7-ESS1-1, A-ESS1-3, A-ESS7-1AR)" ESS1.A: The Universe and Its Stars • "The study of stars' light spectra and brightness is used to identify compositional elements of stars, their movements, and their distances from Earth. (A7-ESS1-1, A-ESS1-3, A-ESS7-1AR)" ESS1.B: Earth and the Solar System • "Cyclical changes in the shape of Earth's orbit around the sun, together with changes in the tilt of the planet's axis of rotation, both occurring over hundreds of thousands of years, have altered the intensity and distribution of sunlight falling on the earth. These phenomena cause a cycle of ice ages and other gradual climate changes. (A7-ESS1-1, A-ESS1-3, A-ESS7-1AR)"

The Next Generation Science Standards (NGSS) is utilized by many states as a framework for teaching science (NGSS Lead States, 2013). In this publication for the high school level, there is a topic named Earth and Space Sciences. This is where the discussion of space physics specific to stellar flares could begin to be introduced. The high school level was chosen as a starting point since solar physics, such as the science discussed in this paper, may be too high of a level to be introduced before then, although there are ways to scale the information to be communicated to an audience of any age. The following table outlines the learning goals and topics as outlined in the NGSS as they related to space science. It should be noted that there will be many similarities between this table and the previous table concerning the Arkansas Astronomy Standards. This is because NGSS is often used as a framework for a state to build their own standards. By including the NGSS standards along with the specialized Arkansas standard, it can be seen how this topic can be applied to high school level students anywhere even despite differences in the exact curriculum used state to state.

Table 6: Next Generation High School Astronomy Science Standards (NGSS Lead States, 2013)	
Student Performance Expectations	Students who demonstrate understanding can: **HS-ESS1-1.** Develop a model based on evidence to illustrate the life span of the sun and the role of nuclear fusion in the sun's core to release energy that eventually reaches Earth in the form of radiation. *[Clarification Statement: Emphasis is on the energy transfer mechanisms that allow energy from nuclear fusion in the sun's core to reach Earth. Examples of evidence for the model include observations of the masses and lifetimes of other stars, as well as the ways that the sun's radiation varies due to sudden solar flares ("space weather"), the 11year sunspot cycle, and non-cyclic variations over centuries.]*
	HS-ESS1-2. Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe.
	HS-ESS1-3. Communicate scientific ideas about the way stars, over their life cycle, produce elements. *[Clarification Statement: Emphasis is on the way nucleosynthesis, and therefore the different elements created, varies as a function of the mass of a star and the stage of its lifetime.]*

	HS-ESS1-4. Use mathematical or computational representations to predict the motion of orbiting objects in the solar system. *[Clarification Statement: Emphasis is on Newtonian gravitational laws governing orbital motions, which apply to human-made satellites as well as planets and moons.]*
Disciplinary Core Ideas	**ESS1.A: The Universe and Its Stars** - The star called the sun is changing and will burn out over a lifespan of approximately 10 billion years. (HSESS1-1) - The study of stars' light spectra and brightness is used to identify compositional elements of stars, their movements, and their distances from Earth. (HS-ESS12),(HS-ESS1-3) - The Big Bang theory is supported by observations of distant galaxies receding from our own, of the measured composition of stars and non-stellar gases, and of the maps of spectra of the primordial radiation (cosmic microwave background) that still fills the universe. (HS-ESS1-2) - Other than the hydrogen and helium formed at the time of the Big Bang, nuclear fusion within stars produces all atomic nuclei lighter than and including iron, and the process releases electromagnetic energy. Heavier elements are produced when certain massive stars achieve a supernova stage and explode. (HS-ESS12),(HS-ESS1-3) **ESS1.B: Earth and the Solar System** - Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. (HS-ESS1-4) **PS3.D: Energy in Chemical Processes and Everyday Life** - Nuclear Fusion processes in the center of the sun release the energy that ultimately reaches Earth as radiation. (secondary to HS-ESS1-1) **PS4.B Electromagnetic Radiation** - Atoms of each element emit and absorb characteristic frequencies of light. These characteristics allow identification of the presence of an element, even in microscopic quantities. (secondary to HS-ESS1-2)

III. Survey of Inservice Teachers and Educational Professionals

In order to better gauge the current need and potential use for a resource on this topic, I surveyed a small group of In-service teachers to see how they would potentially use a resource such as this. To procure these comments and survey respondents, I reached out to several science teaching groups on Facebook to expand my reach. In Table 4, these respondents provided comments on two main questions: (i) whether or not they were currently able to cover the topics of solar flares, exoplanets, and habitability; and (ii) which kinds of resources these teachers look for and use in their classrooms.

Table 7: Comments from Inservice Teachers on Topic Feasibility and Student Preferences	
Name (redacted for privacy)	Comment
Boris [redacted]	"I agree with Jimmy [redacted] that we need more labs on data analysis. I feel a lack of these kinds of work in my class. My strong part is to develop hands-on labs, but data driver ones is my weaker part. Right now I work on the instructions to my lab modeling transit method (be I used it as demo only but now it seems as a good lab)."
Sarah [redacted]	"My Earth and Space class hits on this when we have time and the students are usually pretty interested. I have students who range anywhere from sophomores who don't have the math for Chemistry yet to seniors who are just interested. I have loved using the following website, so anything that could connect to that or expand on it would be great!" https://exoplanets.nasa.gov/eyes-on-exoplanets/#/
Jimmy [redacted]	"Project-based learning topics. Simulations and models. I'd love something using real data and possibly coding."
Amanda [redacted]	"We cover stars and solar flares in my class, but don't have time for exoplanets or habitability."
Tom [redacted]	"It all sounds good! Maybe something on the solar cycle, since it is ramping up now. Everything else you mentioned sounds great too!"

With these comments in mind, I created a survey to send out to ask some more pointed questions about effective astronomy education, topic coverage, and some opinion questions about what resources are most helpful and any frustrations they have when looking for resources.

The questions given are as follows:

i. In your experience, what is the hardest part of teaching different astronomical topics?
ii. When looking for resources to help you better teach astronomy, what catches your eye? For example, do you tend to use more premade labs, infographics, lesson plans etc.?

iii. At a high school or introductory college level, do you have time in the school year or semester to get into topics on stellar flares or habitability?
iv. At a high school or introductory college level, what kind of resource on exoplanets, stellar flares, and habitability would be the most helpful to you and/or your students?
v. Do you find infographics useful in the classroom or as study aids for your students?
vi. In your opinion, where do you see current resources falling short? Are they too in-depth or too surface level to be useful to you?
vii. Do you have any other advice regarding teaching astronomy and/or getting students (high school/college) involved in current research findings?
viii. Do you have any other questions or comments to add? Especially if you have some advice or comments that weren't asked for above. I will take any and all advice you may have.

Below in Table 5, a selected number of responses are reported, however, the complete set of responses can be found in Appendix A. The comments selected in Table 5 are those that proved most helpful in informing the selection of resources recommended for this topic[2].

Table 8: Selected Survey Responses from In-Service Educators and Education Professionals

Question	Comment
i	• "I teach high school astronomy, and my students typically take astronomy over other more math-heavy sciences. So, anything with math/quantitative reasoning really trips them up." - Micah Sittig • "Real astronomy happens at night" – Keith [redacted] • "Students in my class are all at different levels. Some are advanced learners while others are remedial. Finding a balance to engage all students to their level is challenging." – Diana [redacted] • "I end up having a very large range of students in class, so some are deft at the algebra we do. Other students, the algebra is very difficult for them. So I suppose one of the hardest parts is dealing with advanced students, very low math ability students, and everything in-between." – Suzanne Murphy
ii	• "Anything that saves me time, basically it's all planned out and requires easily accessible materials. I'm a busy person/teacher and despite my best intentions, I don't have time to heavily adapt resources made for college students or middle school students to my students, or get exotic resources that are not easily within reach." – Micah Sittig • "I like to use NASA resources. It's a rare course offering in the area, but I happen to know a teacher up in Bentonville that teaches the subject and we shared resources. I also do a lot of projects and, strangely enough, arts integration! My media specialist at the school is a very helpful resource for a lot of my projects." – Suzanne Murphy

[2] In order to be as transparent with bias as possible, the reader should keep in mind that the teachers and professionals that responded to these surveys are among those most interested and involved as well as active as educators on social media. This may not be and likely is not representative of all educators.

iii	• “We cover the basics, but it can't go too deep because it's a survey course that covers astronomy tools, history, solar system, cosmology, spaceflight, etc.” – Micah Sittig • “I have not had time to cover stellar flares! Habitability we do discuss, and we have a project where the students have to pick a place in the solar system to design a colony based on improving habitability.” – Suzanne Murphy
iv	• “Something short or mostly prepared. Using actual data to do data analysis is really good.” – Micah Sittig • “Live events would be awesome! If there were a new exoplanet discovery or a live NASA analysis of a stellar flare, those kinds of current event resources would be awesome!” – Suzanne Murphy
v	• “Yes, I have a lot of posters and visual aids in my classroom. It helps students these days who tend to be very visual learners.” – Micah Sittig • “I do, and in fact I have my students make infographics!” – Suzanne Murphy
vi	• “Too in-depth. Lots of grad students or researchers preparing lessons on specialized topics that don't fit within my high school astronomy broad and shallow survey/introductory curriculum.” – Micah Sittig • “Most resources seem focused on middle school students” - Keith [redacted] • “Most are like finding needles in a haystack. In general, the resources are too in-depth” – Kim Wright • “A mixture of both. Some astronomy resources are directed toward middle school level. Some astronomy resources are geared toward a professional audience that goes over my kids heads. I just wish it were easier and less time-consuming to hunt them down. If I need data or want to explore a case study it takes me a long time to track down exactly what I want to use. I do find plenty of resources that fall within my usability, so I don't think available resources are doing my class a disservice!” - Suzanne Murphy
vii	• “Data analysis/authentic projects really get the kids excited. Working with real/real-time data gets them to feel like they are really "doing astronomy" (which they could be).” – Micah Sittig • “Find a place in your community as a partner! I'm lucky that I've been able to have trips to the University of Arkansas, use a former professor's land out in Elkins as an observatory, use a colleagues land as an observatory, and have Sugar Creek Astronomical society regionally! For being more current, I'm always looking for more connections to bring to the students' attention - if you've got recommendations I'm all ears!” – Suzanne Murphy
viii	• “DO A ROCKET LAB. There are plenty of versions out there, and NASA just released a really affordable version that would be a great intro into projectile variations - I've got the link to NASA CONNECTS (an educator resource community) below. I do a lab every year where they have to build a rocket from scratch and we use geometry on the day of the launch to determine height! It's a lot of time and some groups need extra help, but it's time well-spent! https://nasacentral.force.com/cop/s/”

IV. Recommended Strategy and Selected Resources

One of the major comments made in the survey was that resources that are readily available on the internet are often too in-depth and technical to be helpful or useful to students in high school. On the other side, resources can often be geared to lower grade levels and fail to provide the challenge and depth needed at a high school level. This issue is compounded when you consider the diversity of students' abilities within the classroom. There is no simple answer that will solve this complex issue quickly. Nevertheless, the aid I intend to provide in this paper is a curated list of resources that can help students build a strong foundation for the basics and provide a pathway to grow in complexity. One of the many advantages of structuring this guide in this fashion is that teachers who may use this are able to pick and choose the level of complexity and topics that is appropriate for their individual students. For example, if a teacher observes that their students need more review, the teacher can refer to the resources that aid students in building a strong foundation. Conversely, if a teacher has students that require more challenging material or have time to delve into deeper topics, the teacher can refer to the subsequent sections which provide resources that can push students to grow in their skills and knowledge.

These practical justifications for the organization of this section fall directly in line with the commonly used educational concept of scaffolding which is part of the theory of the Zone of Proximal Development put forth by Lev Vygotsky in 1978. The Zone of Proximal Development refers to "the difference between what a learner can do without help and what he or she can achieve with guidance and encouragement from a skilled partner" (McLeod, 2019) or educator. Vygotsky claimed that allowing students to grow to throw small manageable steps is very effective in helping learners achieve intellectual independence (Kurt, 2020). This is the idea known as scaffolding. More explicitly, according to The Glossary of Education Reform (2015), scaffolding "refers to a variety of instructional techniques used to move students progressively toward stronger understanding and, ultimately, greater independence in the learning process." When students are within the Zone of Proximal Development, students simply need the right "boost" of help in order to learn and achieve their next task or learning goal (McLeod, 2019). Ultimately, this educational theory provided the basis and justification for the structuring of this section. Each resource is laid out to build upon the skills and knowledge from the previous section to encourage the gradual growth in the student's overall knowledge of astronomy. The first section begins with resources to help lay a solid foundation of knowledge for students.

i. Starting with a Solid Foundation

a. Crash Course on Astronomy

Background Resource for Teachers: Oftentimes, science teachers are asked to teach outside of their discipline. For example, it is not uncommon for chemistry teachers to be asked to teach physical science and earth science. This, of course, depends on the resources of the school and its district. The reason for including this caveat of information is to present a resource that would be helpful especially for teachers who may be asked to teach earth science or astronomy who may not have a background in the subject. This is a quick introduction to the topics that those teachers may be teaching. https://www.colorado.edu/fiske/node/987/attachment

b. *Bolstering Students' Quantitative Reasoning*

While students are not necessarily all studying to become astronomers, there is certain math courses that can help students absorb the material faster. The following resource is geared towards students who want to pursue an astronomy career, but the math listed on this page would provide a great way for students to get a leg up on their astronomy courses. https://aas.org/learn/planning-your-education

c. *Classification of Stars*

To help students build a foundation of how stars are classified, this following lesson helps them to understand how stellar classifications are differentiated. This is an incredibly important foundational topic for students to understand before delving any deeper into astronomy. This lesson is a great way to broach this topic with students. https://www.scienceteacherprogram.org/astronomy/DeMizio02.html

d. *What is a Light curve?*

Light curves are an integral part of stellar analysis and current astronomy research. That being said, understanding what they are and what can be learned from them is an essential first step. This website provides a data-centered look at the fundamentals of light curves. https://boyce-astro.org/overview-of-a-light-curve/

e. *Starting with the Sun*

Nova Sun Lab Lesson Plan

- Intended grade level:
- https://myarkansaspbs.pbslearningmedia.org/resource/nvsl.sci.space.lpsl/nova-sun-lab-lesson-plan/

Our Amazing, Powerful Sun Lesson Plan by University of Colorado Boulder

- https://www.teachengineering.org/lessons/view/cub_sun_lesson01

ii. Introducing More Relevant and Complex Topics

With a solid foundation begun, teachers can begin to introduce students to more complex and topics such as stellar flares and habitability. Since students have their foundational knowledge to rely on, they can more confidently engage in topics that challenge and push their current understanding. This section will provide resources that are more specific to the topics addressed by the research presented in earlier sections. These topics include stellar flares, habitability, and the detection of exoplanets.

a. Solar Activity

As previously mentioned, the best way for students to continue to build their framework of knowledge is to allow them to make intentional and incremental steps. If students are leaning towards the zone of independent understanding of the Sun then it is natural for the teacher to move onto topics of solar activity. The following lessons discuss one version of solar activity which comes in the form of solar storms.

Modeling Solar Storms

- Intended grade level: Middle School – 5th Grade
- https://greatbasinobservatory.org/lesson-plans/modeling-solar-storms

b. Stellar Flares

There is a greater number of resources related specifically to solar flare as opposed to stellar flares on stars far from our solar system. The National Solar Observatory in Boulder, Colorado is a great resource to consult on a wide array of topics related to the solar activity such as solar flares. In the case of this research project, the focus was on stellar flares of stars millions of miles away, however, it is oftentimes more beneficial to students to begin by learning these topics on objects they are more familiar with and interact with on a daily basis, such as the Sun. Because of this, I recommend beginning talking about stellar activities such as sunspots, prominences, flares, and coronal mass ejections in terms of the Sun. This allows students to create a foundation that can be built upon later. This webpage https://nso.edu/for-public/educators-old-page/stembox/ has a host of solar physics topics. Most specifically, under the Solar Science section, there is a resource on Solar Observations with accompanying worksheets and real-world videos geared for grade levels 5-9.

c. Exoplanet Detection and Habitability

Exoplanets are generally a fun topic for students to discuss because it usually entails talking about the potential of alien life. This NOVA Exoplanet lab is an exciting way to engage students in the lesson. Students who partake in this lab will be hunting for planets through the use of real techniques astronomers use such as transit and radial velocity data to detect planets as well as analyzing data to learn about a planet's atmosphere who could greatly impact the habitability. https://myarkansaspbs.pbslearningmedia.org/resource/nvexl-sci-exoplanetlab-lessonplan/nova-exoplanet-lab-lesson-plan/

iii. Connecting Students to the Real World through Simulations and Data

A critical point brought up by several survey respondents was the difficulty in teaching astronomy effectively when it is best observed at night, far outside of school hours. This is a widespread difficulty noted by many astronomy educators. There are many approaches that teachers have taken to address this issue from field trips to requiring students to do night observations, to providing hands-on ways to study the Sun – which is visible during school hours. These experiences are invaluable to students because hands-on activities help them to make sense of the scientific concepts within their own personal framework of understanding the world. The more that the science they do within a classroom connects to the world they see in their everyday lives, the more lasting impact that knowledge will have on these students. In this section, I propose two ways for teachers to connect their students to the real world: (1) through online simulations and software, and (2) through using and collecting real world data in their work.

a. Online Modeling

The Star in a Box simulation by Las Cumbres Observatory is a particularly fun way to allow students to apply their knowledge of stellar classifications and the HR diagram in the investigation of an unknown star. Additionally, this lesson is ready-made for different levels of students by providing presentations and worksheets for students at different levels. While it is specifically geared toward UK curriculum, the ideas are easily applied to the standards listed earlier. https://lco.global/education/activities/star-in-a-box/#:~:text=Star%20in%20a%20Box%20is,little%20for%20billions%20of%20years.

b. Resources with Real-World Data

The Solar Dynamics Observatory has created this thirty-page resource on how to use data from the Solar Dynamics Observatory within the classroom. From background material to student videos and worksheets, to instructions on how to access live data, to assessment recommendations, this guide is a great way to start bringing current astronomy data into the classroom at any level. http://solar-center.stanford.edu/activities/SDO/Chabot-SDO-Data-in-the-Classroom.pdf

c. Citizen Science Projects

Lastly, citizen science is a critical and prevalent way to connect the knowledge your students are learning in the classroom to work being done in current astronomy. Citizen science projects take this one step further by allowing students to collect data themselves to aid scientists. Here is a link to multiple NASA-recommended citizen science projects that all relate to exoplanets and TESS data. https://exoplanets.nasa.gov/citizen-science/#:~:text=This%20citizen%20science%20platform%20allows,Exoplanet%20Survey%20Satellite%20(TESS).&text=The%20public%20is%20invited%20to,to%20learn%20how%20planets%20form.

The project that I would like to highlight to relate to this project is the Zooniverse project searching for exoplanets within TESS data. The planets found by looking at these light curves could be just that planet that gives the best-case scenario in terms of habitable conditions on the planet. This project teaches students what an exoplanet transit would look like in data and allows them to actively search reach light curves for these signatures. https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess

I. Conclusions

The number of resources available on the internet relating to astronomy is practically endless. However, it is my hope that the resources selected for this paper give educators a plan on how to approach teaching science in their classrooms in a more strategic fashion. The resources were not simply chosen to fill a quota but to directly address the concerns from educators whose comments I included earlier. This resource is not an end-all be-all of the good resources, but a framework that can be emulated with any astronomy topic to help organize and orient teachers to teacher astronomy effectively. With the intense constraints that are imposed on teachers by a limited school year and specific curriculum, it can often seem difficult to teachers to find fun and engaging work for their students, however, in cultivating this resource and learning from current teachers, I have seen that many good teachers are able to achieve it all and I hope this resource can alleviate that burden off of teachers to allow them the tools to better reach their students.

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Appendix A: Complete Educator Survey

This section presents the full and unedited survey that was completed by several in-service teachers and education professionals. Some of these answers were utilized in the writing of this paper. The questions regarding identifying information and privacy requests have been omitted. Names are only used when given explicit permission by the respondent.

The questions given are as follows:

ix. In your experience, what is the hardest part of teaching different astronomical topics?

x. When looking for resources to help you better teach astronomy, what catches your eye? For example, do you tend to use more premade labs, infographics, lesson plans etc.?

xi. At a high school or introductory college level, do you have time in the school year or semester to get into topics on stellar flares or habitability?

xii. At a high school or introductory college level, what kind of resource on exoplanets, stellar flares, and habitability would be the most helpful to you and/or your students?

xiii. Do you find infographics useful in the classroom or as study aids for your students?

xiv. In your opinion, where do you see current resources falling short? Are they too in-depth or too surface level to be useful to you?

xv. Do you have any other advice regarding teaching astronomy and/or getting students (high school/college) involved in current research findings?

xvi. Last, optional question: Do you have any other questions or comments to add? Especially if you have some advice or comments that weren't asked for above. I will take any and all advice you may have.

Table 9: Complete Survey Responses from In-Service Educators and Education Professionals	
Question	**Comment**
i	• "I teach high school astronomy, and my students typically take astronomy over other more math-heavy sciences. So, anything with math/quantitative reasoning really trips them up." - Micah Sittig • "Real astronomy happens at night" – Keith [redacted] • "Students in my class are all at different levels. Some are advanced learners while others are remedial. Finding a balance to engage all students to their level is challenging." – Diana [redacted] • Providing hands-on activities
ii	• "Anything that saves me time, basically it's all planned out and requires easily accessible materials. I'm a busy person/teacher and despite my best intentions, I don't have time to heavily adapt resources made for college students or middle school students to my students, or get exotic resources that are not easily within reach." – Micah Sittig

	• I like to use student-centered investigations that I either make or adapt from others • Online activities • labs and activities that I can adjust easily for my population.
iii	• “We cover the basics, but it can't go too deep because it's a survey course that covers astronomy tools, history, solar system, cosmology, spaceflight, etc.” – Micah Sittig • No • Habitability, We mention flares but don't go into them • Briefly
iv	• “Something short or mostly prepared. Using actual data to do data analysis is really good.” – Micah Sittig • Student-centered inquiry activities • online labs ad simulations • premade labs and activities
v	• “Yes, I have a lot of posters and visual aids in my classroom. It helps students these days who tend to be very visual learners.” – Micah Sittig • Yes • No
vi	• “Too in-depth. Lots of grad students or researchers preparing lessons on specialized topics that don't fit within my high school astronomy broad and shallow survey/introductory curriculum.” – Micah Sittig • “Most resources seem focused on middle school students” - Keith [redacted] • “Most are like finding needles in a haystack. In general, the resources are too in-depth” – Kim Wright • both depending on the resource
vii	• “Data analysis/authentic projects really get the kids excited. Working with real/real-time data gets them to Mixing the interesting with the foundational concepts • No • including current events and data • feel like they are really "doing astronomy" (which they could be).” – Micah Sittig
viii	• No responses were received.

Appendix B: Python Code

In an effort to promote transparency and accessibility within the field of astronomy research, the entire code used for this project is presented below. This code goes from the ground floor of downloading the TESS data, to flagging the flares, and finally performing the flare fitting using a form of Markov-Chain Monte-Carlo fitting. There are an array of comments throughout the code to aid in understanding the functions that each portion performs.

```
"""
Created on Fri Apr  8 23:55:02 2022

@author: aelie, paulb

 This is a tutorial to download available TargetPixelFile objects found here:
 https://heasarc.gsfc.nasa.gov/docs/tess/Target-Pixel-File-Tutorial.html

 The purpose of this code is to:
   - Pull the target pixel files (tpf) for each of the candidates
   - Pull all tpf's of each candidate that have the 2 minutes (120 s) cadence irrespective of sector
      - This code neglects all of the 20 second observations

 Lightkurve citation call: lk.show_citation_instructions()
"""
# Import necessary packages
import lightkurve as lk
import matplotlib.pyplot as plt
from lightkurve import PLDCorrector
import astropy.table
from astropy import units
from astropy.io import fits
import numpy as np
import emcee
from itertools import groupby
from operator import itemgetter
from scipy.optimize import minimize
from scipy import stats
import scipy as sp
from scipy.interpolate import interp1d
import corner
import sys

""" Beginning of Callable Code"""
average_PDC_corrections = []

# Gunther Candidate TEST – a good flare to try
#i = str('TIC 144217628')

# Bonney et al., 2019 Candidates
#i = str("TIC 12421862")
i = str("TIC 141527579")
#i = str("TIC 153065527")
#i = str("TIC 165551882")
```

```
#i = str("TIC 259962054")
#i = str("TIC 305048087")
#i = str("TIC 36724087")
#i = str("TIC 429358906")
#i = str("TIC 467179528")
#i = str("TIC 92226327")

# Uses lightkurve to pull the target pixel files (only from TESS)
search_result = lk.search_targetpixelfile(i, mission='TESS', author='SPOC')
result = search_result

correct_cadence = '[120.] s'

for row in search_result:
    cadence = str(row.exptime)
    if cadence == correct_cadence:
        print("pulled tpf file!!!")

        # Downloads the TPF file
        tpf = row.download(quality_bitmask='default')
        print(tpf)

        # Plots the tpf file
        tpf.plot()
        #plt.savefig(i + '_initial_tpf_' + str(tpf.sector))
        tpf.get_header(ext=0)['Sector']

        # Set of keywords and values that can be pulled
        sector = tpf.sector
        mission = tpf.mission
        ra = tpf.ra
        dec = tpf.dec
        hdu = tpf.hdu
        time = tpf.time
        camera_number = tpf.camera
        ccd = tpf.ccd
        ppln_msk = tpf.pipeline_mask
        flux = tpf.flux
        flux_err = tpf.flux_err
        flux_bkg = tpf.flux_bkg
        flux_bkg_err = tpf.flux_bkg_err

        # Plot Lightcurve
        uncorrected_lc = tpf.to_lightcurve(aperture_mask='threshold')
        uncorrected_lc.errorbar()
        uncorrected_lc.plot()
        plt.show()
        #plt.savefig(i + '_lightcurve_b4_corrections_' + str(tpf.sector))

        """ Corrections - Pixel Level Decorrelation """
        """ tutorial found here: https://docs.lightkurve.org/tutorials/2-creating-light-curves/2-3-k2-
pldcorrector.html"""

        pld = PLDCorrector(tpf)
        lc = pld.correct() # corrected lightcurve
        diagnose = pld.diagnose()
```

```
    diagnose[0].plot()
    plt.show()
    #plt.savefig(i + "_PLDcorrected_lc_" + str(tpf.sector))
    lc = lc.remove_nans()

    # how much did it actually correct?
    #difference = uncorrected_lc - lc
    #difference.plot()
    #plt.savefig(i + '_Difference_due_to_corrections')
    #difference_sum = sum(difference['flux'])
    #avg_correction = difference_sum.value / len(difference['flux'])
    #average_PDC_corrections.append(avg_correction)

    """ Flatten Lightcurve """
    flat_lc = lc.flatten(window_length=1001) #need to normalize to zero, how? loop over maybe - but
need to replace values in Lightcurve object
    #flat_lc.flux.value = flat_lc.flux.value - 1
    flat_lc.plot()
    #plt.savefig(i + '_flattened_lc_' + str(tpf.sector))
    plt.show()
    #for x in range(len(flat_lc['flux'].value)):
        #flat_lc['flux'].value = flat_lc[x] - 1

    # Plot Background flux
    bkg = tpf.get_bkg_lightcurve()
    bkg.plot()
    plt.show()
    #plt.savefig(i + "_background_flux_" + str(tpf.sector))

    """ Flare Flagging Code """
    fl_t_arr = []
    flare_time = []
    #arr = np.array(lc_fits)

    flt = 3   # number of consecutive time steps we want (3 = 6 minutes bc of 2 min cadence)
    flux = flat_lc.flux.value #flux is in electrons/s
    flux -= 1 #CHECK IT HERE
    time = flat_lc.time.value
    flux_err = flat_lc.flux_err.value
    st_dev = np.std(flux, out=None)
    threshold = 3 * st_dev
    mean = np.average(flux)

    fl_ct = 0
    for t in range (len(time)):

        if flux[t] >= threshold + mean:
            fl_ct += 1
        else:
            if fl_ct != 0:
                flare_time.append(fl_ct)
            # mulitply by 2 rough time; can compare at end +-2min
            fl_ct = 0
        if fl_ct == flt:
            prev=[x+1 for x in np.arange(t-flt, t)]
            for p in prev:
```

```
        fl_t_arr.append(p)
    elif fl_ct > flt:
        fl_t_arr.append(t)


print(fl_t_arr)


fl_prop = []
fl_sted = []
fl_st = 0
fl_ed = 0
for t in range(len(fl_t_arr)):

    try:
        abc=fl_t_arr[t + 1]
    except IndexError:
        abc=0

    if fl_st == 0:
        fl_st = fl_t_arr[t]
        fl_st_t = t

    elif abc-fl_t_arr[t] > 1:

        fl_ed = fl_t_arr[t]
        fl_x = fl_t_arr[fl_st_t:t+1]
        flare_length = len(fl_x) * 2

        flare_flux_ = flux[fl_st-5:fl_ed+6]
        peak_fl_flux = max(flare_flux_)
        # need time array value for the max
        flare_time_ = time[fl_st-5:fl_ed+6]
        flare_flux_err_ = flux_err[fl_st-5:fl_ed+6]
        fl_sted.append([fl_st,fl_ed])

        #Plot flare
        plt.plot(flare_time_, flare_flux_)
        plt.title("Potential Flare from " + str(i) + " lasting " + str(flare_length) + " minutes ")
        plt.savefig("Flare_"+str(i)+'_'+str(fl_st)+'_'+str(fl_ed))
        plt.show()

        """
        Flare Fitting Code Using EMCEE - append output to fl_prop
        """
        #GET FLARE DATA ITERITIVELY
        flare_fl = flare_flux_
        flare_t = flare_time_

        #fake noise:
        flare_n = np.sqrt(1+np.abs(flare_fl))-1

        fl_start=  flare_t[5]
        fl_dur = len(flare_t-10)
        fl_m = np.max(flare_fl)
        fl_m_times = np.where(flare_fl == fl_m)
```

```
fl_m_sig = flare_flux_err_[fl_m_times[0][0]] #assuming 1 flare time
for i in fl_m_times:
    fl_m_time = i[0]
    print(fl_m_time)

#tn is how many time steps to include, default=10000

#use the commented out code to set tn to 100* your number of time steps
#recommend to cut out a postage stamp of ~100 time steps around the flare anyway
tnum=len(flare_time_)
tnum=100 #currently hard-coded to 10000
tn=tnum*100

#lightcurve data goes here (x=time; y=flux) normalized to 0
x = flare_time_
y = flare_flux_
y_err = flare_flux_err_

#returns the interpolated peak, its occurance time, and the fwhm time
def fwhm_n0(x,y):
    terp=interp1d(x,y,kind='cubic')
    tx=np.arange(x[0],x[-1],(x[-1]-x[0])/tn)
    ty=terp(tx)
    peak=np.max(ty)
    peak_i=int(np.where(ty==peak)[0])
    l_x=0
    r_x=0
    for n in reversed(range(len(tx[:peak_i]))):
        if ty[n] <= 0.5*peak:
            l_x=tx[n]
            break
    for n in range(len(tx[peak_i+1:])):
        if ty[n+peak_i+1] <= 0.5*peak:
            r_x=tx[n+peak_i+1]
            break
    t_half=(r_x-l_x)
    return peak, tx[peak_i], t_half, [l_x,r_x]

w, v, q, z = fwhm_n0(flare_t, flare_fl)

#these are median valuesfor the first flare on TIC 144217628
#you will use emcee to pick these values and use them as an argument to flare_mod
theta_mu=[fl_m,
      q,
      v,
      1.941,
      -0.175,
      -2.246,
      -1.125,
      0.6890,
      -1.6,
      0.303,
      -0.2783,
      ]
theta_mu=np.array(theta_mu)
theta_sig=[fl_m_sig,
```

```
    0.00138889, #2 minutes in day units
    0.00138889,
    0.008,
    0.032,
    0.039,
    0.016,
    0.0008,
    0.003,
    0.0009,
    0.0007
    ]
theta_sig=np.array(theta_sig)
#time here is in t_1/2 units
#assumes normalized to 0 (i.e. mean ~= 0.0)
def flare_mod(theta=theta_mu):
    f_max,fwhm,T,a,b,c,d,e,f,g,h = theta
    t1=np.arange(-1,0,1/tn)
    t2=np.arange(0,6,6/tn)
    F=[1+(a*t1)+(b*t1**2)+(c*t1**3)+(d*t1**4),(e*np.exp(f*t2))+(g*np.exp(h*t2))]
    F=np.concatenate(F)
    Flux=F*f_max
    Time=(np.concatenate([t1,t2])*fwhm)+T
    return Flux,Time

def log_likelihood(theta, x, y, yerr):
    l, m  = flare_mod(theta=theta)
    #This is training wheels for the model, can't let it get too far out of bounds
    if np.max(l) > fl_m + (6*fl_m_sig) or np.min(l) < 0.:
        return 0.

    #Define an interpolant object
    fl_interp=sp.interpolate.interp1d(m, l, kind='cubic', fill_value=0., bounds_error=False)
    #Evaluate the interpolant at true time (x). The optional arguments in interp1d are necessary to
do this

    fl_ttime=fl_interp(x)

    sigma2 = yerr ** 2 + fl_ttime ** 2 #+ 2 ** 2 + 6 ** 2
    likelihood = -0.5 * np.sum((((y - fl_ttime) ** 2) / sigma2) + np.log(2*np.pi*sigma2))
    #sigma2 = yerr ** 2 + l ** 2 + 2 ** 2 + 6 ** 2
    #likelihood = -0.5 * np.sum((y - l) ** 2 / sigma2 + np.log(sigma2))
    return likelihood

def normpdf(x, mu, sigma):
    #If theta is within reasonable bounds, return pdf, otherwise return -inf
    u = (x-mu)/abs(sigma)
    y = (1/(np.sqrt(2*np.pi)*abs(sigma)))*np.exp(-u*u/2)
    return y

def log_prior(x,mu=theta_mu,sigma=theta_sig):

    u = (x-mu)/abs(sigma)
    y = (1/(np.sqrt(2*np.pi)*abs(sigma)))*np.exp(-u*u/2)

    return np.sum(np.log(y))

def log_probability(theta, x, y, yerr):
```

```
        lp = log_prior(theta)
        #if not np.isfinite(lp):
            #return -np.inf
        probability = lp + log_likelihood(theta, x, y, yerr)
        return probability

    #pos = (1e-4 * np.random.randn(32, 11)) + np.array(theta_mu)[np.newaxis,:]
    #nwalkers, ndim = pos.shape
    #sampler = emcee.EnsembleSampler(nwalkers, ndim, log_probability, args=(x, y, y_err))
    #sampler.run_mcmc(pos, 7000, progress=True)


    """ Testing for Results Plots """
    # Original Flare Plot
    plt.plot(flare_time_, flare_flux_)
    plt.title("Potential Flare from " + str(i) + " lasting " + str(flare_length) + " minutes ")
    plt.xlabel("Flux electrons/sec")
    plt.ylabel("Time BJD")
    plt.savefig("Flare_"+str(i)+'_'+str(fl_st)+'_'+str(fl_ed))
    plt.show()

    # Model Data
    flat_samples = sampler.get_chain(discard=500, flat=True)
    median = np.median(flat_samples, axis=0)
    print(flat_samples)
    Flux, TIme = flare_mod(median)


    # Corner Plots
    labels = ["fl_m", "fwhm", "fl_m_time", "a", "b", "c", "d", "e", "f", "g", "h"]
    fig = corner.corner(flat_samples, labels=labels)


    # Plots to overlay data and model output
    fig, ax = plt.subplots()
    plt.errorbar(x, y, yerr=y_err, fmt='-o')
    plt.plot(x, y)
    plt.plot(TIme, Flux)
    plt.show()



    inds = np.random.randint(len(flat_samples), size=13)
    for ind in inds:
        sample = flat_samples[ind]
        plt.plot(x, np.dot(np.vander(x, 2), sample[:2]), "C1", alpha=0.1)
    #plt.set_xlabel('Time BJD')
    #plt.set_ylabel('Flux (ergs/s)')
    #plt.set_title('Line plot with error bars')
    plt.show()


    fl_st=0

print('observation done.  onto next row')
```