

XV. Stellar Flares Introduction:

Stellar Flares: Power bursts of energy from stars resulting from magnetic fields. Almost all stars in the Universe with convection zones produce stellar flares - bursts of energy emitted from the star that are thought to be caused by magnetic reconnection.

Light Curve File: Time series data for a target pixel file of a specific star that shows the change in brightness. Light curves are saved as text files, with 10 columns and two header lines.

A Light Curve flare characteristic is a **rapid rise followed by a slow decline process.**

Our Sun is a G-type star, or “yellow dwarf.” It has a rotational period approximately 25 days at its equator, but varies depending on latitude, with the polar regions taking longer to rotate, reaching up to 35 days; this phenomenon is called differential rotation. G defined by strong absorption lines from ionized calcium; more generally, absorption lines from metals are stronger in G-type stars than in hotter stars (such as F-type stars) and weaker than in cooler stars (such as K-type stars). G-type stars have typical (effective) temperatures between around 5200 Kelvin (K) and 6000 K. Our sun is an old star ≈ 10 GYr.

Red dwarfs (or M-dwarf) are by far the most common type of fusing star in the Milky Way. A red dwarf is the smallest kind of star on the main sequence with **2000 to 3,900 K temperature and 0.08 to 0.6 M_{\odot} mass.** M-dwarfs make up 75% of nearby stars.

Flare Properties of Small Stars

The amplitude of stellar flares from small stars (such as red dwarfs or other low-mass stars) tends to decrease with increasing mass and temperature for several reasons. This phenomenon is related to the way magnetic activity, which drives stellar flares, is influenced by the star's mass and internal properties. Explosion of stellar flares can release enormous energy, mainly caused by the magnetic reconnection process in the coronal region.

1. Magnetic Activity and Stellar Mass:

Low-Mass Stars (Red Dwarfs):

Low-mass stars are typically more active magnetically. These stars have stronger magnetic fields relative to their size, which means they are more prone to flare activity. The magnetic dynamo in low-mass stars (the process that generates their magnetic field) operates more efficiently due to their relatively slower rotation rates, higher levels of magnetic flux, and a more vigorous convective envelope.

High-Mass Stars:

Higher-mass stars (such as G-type or A-type stars) have weaker magnetic fields and less intense convection, which means they generate fewer flares. Their magnetic dynamos tend to be less efficient, and because they rotate faster, the magnetic activity is often more evenly spread out over the star's surface, preventing highly energetic flares. Essentially, these stars are less magnetically active overall.

Effect on Flare Amplitude: Low-mass stars (e.g., red dwarfs) experience frequent, intense flares because of their strong magnetic fields, higher-mass stars experience fewer, less intense flares due to weaker magnetic activity.

2. Temperature and Stellar Activity:

Cooler Stars:

Cooler, lower-mass stars (like red dwarfs) have deeper convection zones. These convection zones, combined with the star's relatively slow rotation, create large, localized magnetic fields that can produce powerful flares. The cool Temperature allow for more pronounced magnetic field interactions at the surface, leading to stronger flares.

Hotter Stars:

As a star's mass increases, it tends to be hotter, and this increases its luminosity and temperature.

For these hotter stars (e.g., F-type, G-type), the convective regions are smaller and less dynamic, which means that the magnetic field generation is weaker. Hotter stars also tend to rotate more quickly, which can cause their magnetic fields to become less concentrated in localized regions and reduce flare activity.

Effect on Flare Amplitude: As temperature increases, the star's magnetic field becomes less effective at producing high-amplitude flares. The smaller convection zones in hotter stars limit the intensity of the magnetic activity that drives flares.

Rotation Rate: Slower Rotators:

Small, low-mass stars **like red dwarfs** typically rotate **more slowly** compared to more massive stars. This **slower rotation** allows for a **more stable and concentrated magnetic field**, which can result in more frequent and intense flare events.

Faster Rotators:

More massive stars tend to rotate faster. The fast rotation leads to a more diffuse magnetic field, which, while still present, is not as concentrated in specific regions. This reduces the likelihood of intense flare events since the magnetic field is more spread out and less prone to the localized instabilities that cause flares.

Effect on Flare Amplitude:

The slower rotation in low-mass stars helps build up stronger magnetic fields that can lead to large, energetic flares. In higher-mass stars, the faster rotation leads to more spread-out, weaker magnetic fields, and hence weaker flares.

4. Star's Life span and Magnetic Activity: Red Dwarfs

Low-Mass Stars:

These stars have long lifetimes, often on the order of tens to hundreds of billions of years. Their magnetic fields remain active throughout their long lives, and they continue to experience flares. They are also more prone to "flare events" because of their strong, active magnetic dynamos.

Higher-Mass Stars:

These stars have shorter life spans, and their magnetic activity typically wanes more quickly as they age. As they exhaust their nuclear fuel, the mechanisms that generate strong magnetic fields become less effective. Thus, their flare activity decreases with age.

Mass and Temperature Effects:

As stellar mass and temperature increase, the star's magnetic activity decreases because:

More massive stars have weaker magnetic fields and less efficient magnetic dynamos.

Hotter stars have smaller convection zones, which limits the dynamo's efficiency and reduces flare activity.

Faster rotation in more massive stars results in more diffused magnetic fields, leading to weaker flares.

Thus, the amplitude of stellar flares tends to decrease as both stellar mass and temperature increase: Primarily due to the diminished strength of the magnetic activity that drives flare events in these stars.

Light curves for Exoplanet Survey Data

For a comprehensive description of all known Exoplanets refer to the NASA Exoplanet Archive:

https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=PS&constraint=default_flag=1&constraint=disc_facility+like+%27%25TESS%25%27

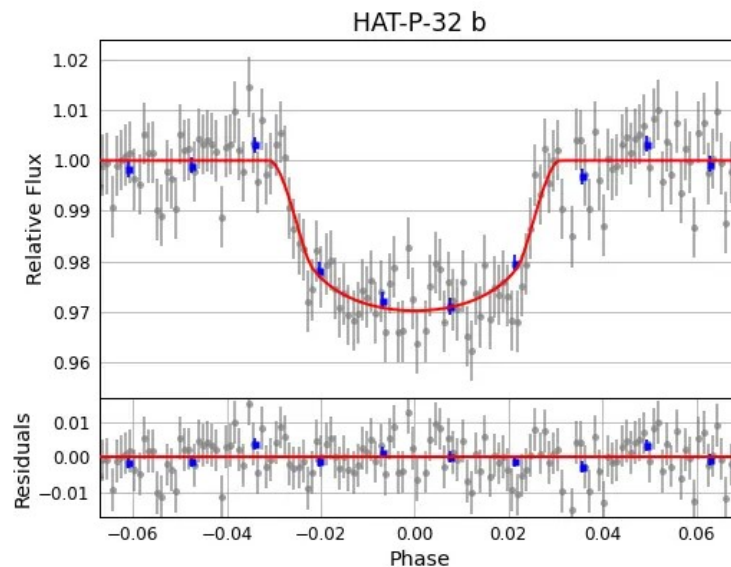
Exoplanet light curve

<https://exoplanets.nasa.gov/exoplanet-watch/about-exoplanet-watch/background/>

A light curve can show the change in brightness of a star when an exoplanet passes in front of the star. We can't see the exoplanet directly using the transit method, but we can see the effect the exoplanet has on its star's brightness as it transits.

The horizontal part of the light curve is the baseline brightness of the star when there are no exoplanets passing in front of it. The dip in the light curve shows the star's light blocked by the exoplanet during the transit. The deeper the dip, the more light is blocked, the bigger the planet. If you observe the same star over many nights, you can see how often the star's light is blocked by a transiting exoplanet. The more frequently these transits occur, the shorter the year is for the exoplanet, and the hotter the planet is. By looking at light curves, you can even tell whether the planet has a thick atmosphere.

When we create light curves, we compare the brightness of the target star with the brightness of a few nearby comparison stars, or comp stars. It's important to choose comp stars that are not variable stars (stars whose brightness changes over time), so we use star charts from the American Association of Variable Star Observers (AAVSO) to help us identify stars with stable brightness to compare with our target star.



"Detrending data" means to **remove any noticeable trend or pattern (usually a linear increase or decrease)** from a dataset, effectively **leaving behind only the fluctuations around that trend**, allowing for a **more focused analysis on the variability** within the data **without the influence of the overall trend line**; this is typically achieved by **fitting a line to the data** and **subtracting that fitted line** from the original data points.

The flare energy is calculated using the following equation

$$E_{\text{flare}} = 4\pi R_{*}^2 \sigma_{\text{SB}} T_{*}^4 \int F_{\text{flare}}(t) dt$$

Mikulski Archives - Space Telescopes

The Mikulski Archive for Space Telescopes (MAST) is an astronomical data archive focused on the optical, ultraviolet, and near-infrared. MAST hosts data from over a dozen missions like Webb, Hubble, Kepler, Transiting Exoplanet Survey Satellite (TESS), and in the future Rome.

TESS's two-year all-sky survey would focus on nearby G-, K-, and M-type stars with apparent magnitudes brighter than magnitude 12 and 1,000 of the closest red dwarfs.

MAST TESS Transients Light Curve Files

<https://tess.mit.edu/public/tesstransients/pages/readme.html>

TESS periodically reads out entire frame of all four cameras, nominally every 30 minutes (below says 10 minutes).

MAST Light Curve File Text Format

	BTJD	TJD	cts_per_s	e_cts_per_s	mag	e_mag	bkg
TJD		TESS Julian date, equal to Julian Data, JD - 2457000					
BTJD		Barycentric TESS Julian Date (Day + Fraction of Day) - Relativistic coordinate time scale					
cts_per_s		Flux light curve in counts per second (photoelectrons per second).					
e_cts_per_s		Uncertainty in cts_per_s (1-sigma).					
mag		Light curve in TESS magnitudes (see Flux Calibration).					
e_mag		Uncertainty in mag (1-sigma). A value of 99.9 marks a 3-sigma upper limit.					
bkg		Local background in differential counts.					

Get Data: $LCF := READPRN("lc_2022sfe_cleaned\ No\ Header.txt")$

$cols(LCF) = 7$ $rows(LCF) = 3760$

Choose 12 Days to View

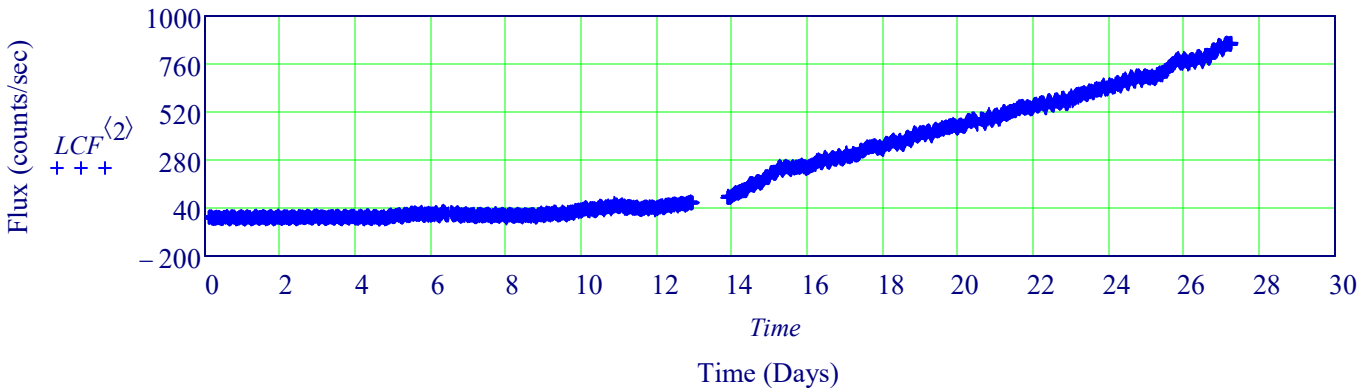
$Mag := LCF^{(4)}$ $Time := LCF^{(1)} - 2797$ $Days := Time_{3759} - Time_0 = 27.16$ $Time_{1900} = 14.264$
 $Time_{2800} = 20.597$

TESS Measurement Interval: $(Time_1 - Time_0) \cdot 24 \cdot 60min = 9.994 \cdot min$

Sample 12 Days of Data: $LCF_{12} := submatrix(LCF, 0, 1700, 0, 6)$ $Time_1 := LCF_{12}^{(1)}$

$min(LCF_{12}^{(2)}) = -17.002$ $max(LCF_{12}^{(2)}) = 67.942$

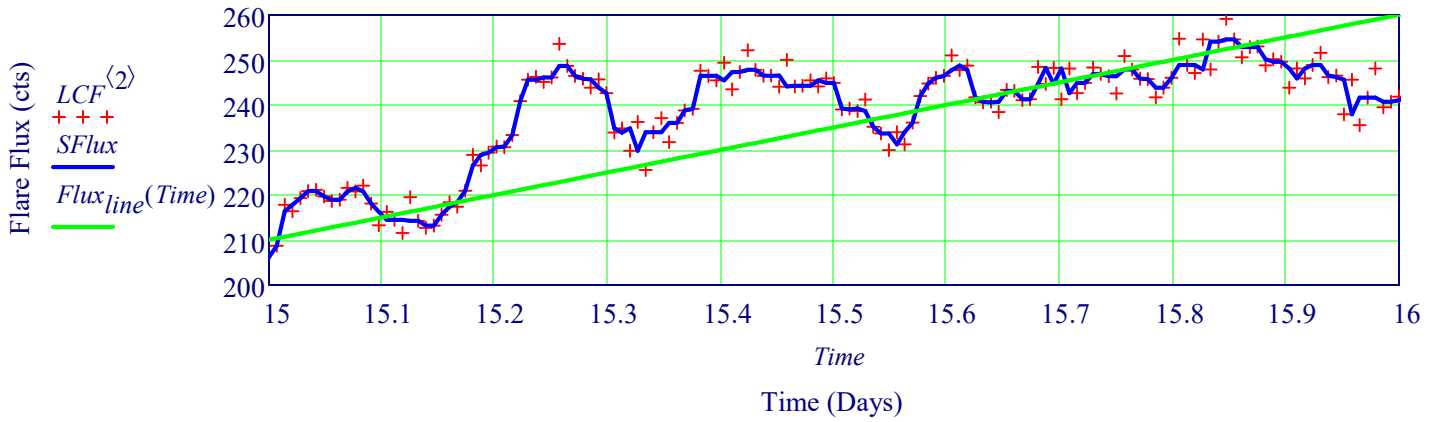
TESS Flare Flux (photo electron counts/sec) vs. Time (Days)



Detrend Data Reference Line: $Flux_{line}(tt) := 210 + 50 \cdot (tt - 15)$

Use Median Value to Smooth Flux Curve $SFlux := medsmooth(LCF^{(2)}, 3)$

TESS Flare Flux (photo electrons/sec) vs. Time (Days)



Flare Magnetic Activity and Physical Parameters of Exoplanet Host Stars

*Based on LAMOST DR7, TESS, Kepler, and K2 Surveys,
The Astrophysical Journal Supplement Series, 261:26 (20pp), 2022 August*

Data Columns: ID PeakTime Begin End Duration Amplitude Teff Radius Energy

$TDat := READPRN("Data\Flare Parameters of Exoplanet System of TESS.txt")$

$KDat := READPRN("Data\Flare Parameters of Kepler.txt")$

$K2Dat := READPRN("Data\Flare Parameters of K2.txt")$

$TK2 := stack(TDat, KDat, K2Dat)$

$temp := TK2^{(6)}$

$Radius := TK2^{(7)}$

$R := line(temp, Radius)$

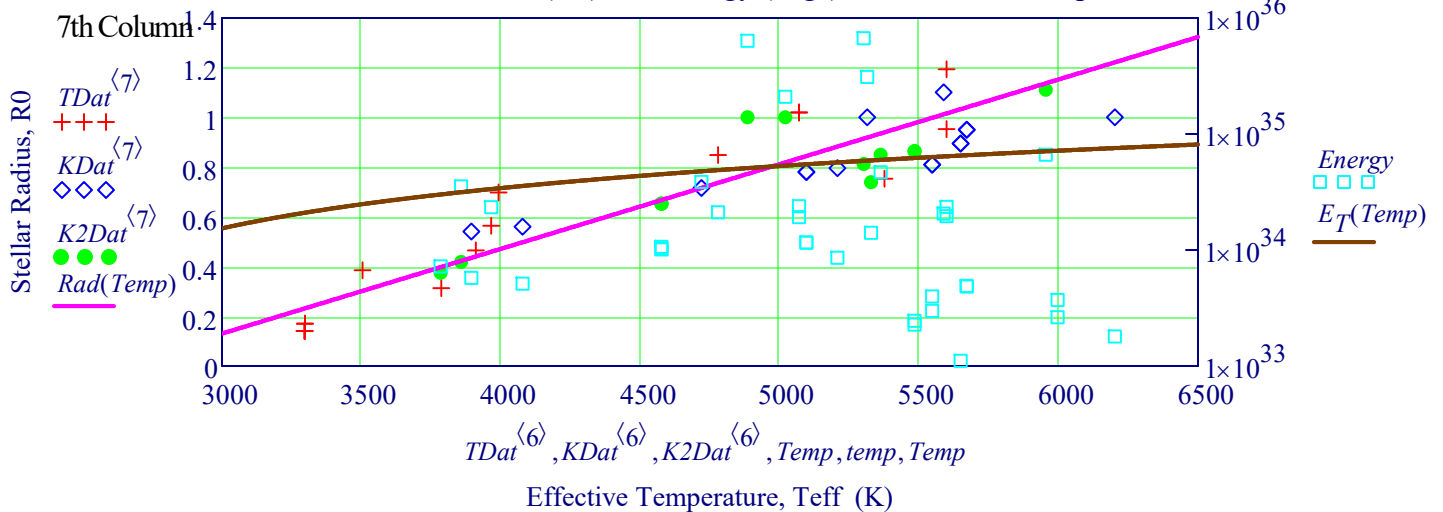
$Rad(t) := R_0 + R_1 \cdot t$

$Energy := TK2^{(8)}$

$E := expfit(temp, Energy)$

$E_T(T) := E_0 \cdot exp(E_1 \cdot T) + E_2$

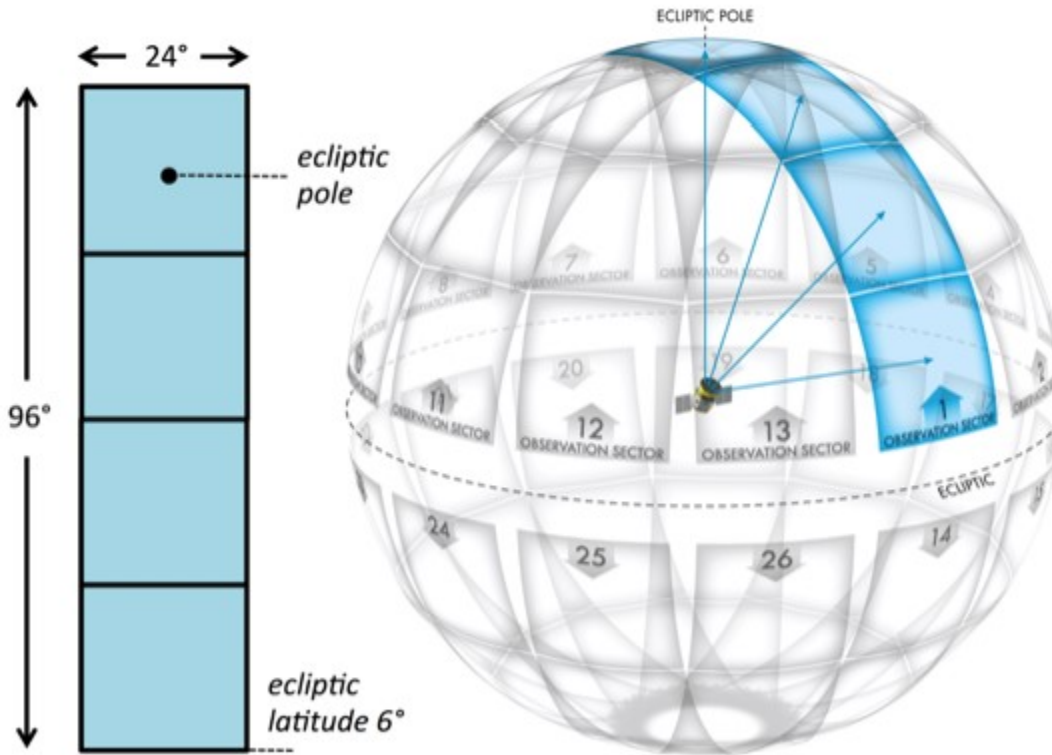
Radius is the 7th Column Relation Stellar Radius (R0) and Energy (Ergs) vs. Effective Temperature



Intro to TESS

The Transiting Exoplanet Survey Satellite (TESS) is a NASA-sponsored Astrophysics Explorer-class mission that is performing a near all-sky survey to search for planets transiting nearby stars. TESS completed its primary mission in July of 2020, and has now entered its extended mission. The current extended mission will last until September 2022, and will continue to scan the sky for exoplanets and transient events. The TESS mission is now more community focused with a larger guest investigator (GI) program.

Over the last three years TESS has observed both the northern and southern hemispheres, with each hemisphere being split into ≈ 13 sectors. Each sector is observed for ≈ 27 days by TESS's four cameras.



The main data products collected by the TESS mission are described below.

Full Frame Images (FFIs): The full sector images, with a cadence of 30-min (years 1 & 2) or 10-min (years 3 & 4).

Target Pixel Files (TPFs): Postage stamp cut outs from the FFIs, focused on a selected target of interest. Each stamp has a cadence of 2-min or 20-sec.

Light Curve Files (LCFs): The time series data produced for each 2-min or 20-sec TPF object.

Info on the TESS mission and its data products, available at TESS GI pages.

Light Curve Data Sources

<https://exoplanetarchive.ipac.caltech.edu/>

<https://heasarc.gsfc.nasa.gov/docs/tess/TESS-Intro.html>

Lightkurve

Lightkurve offers a user-friendly way to analyze time series data obtained by telescopes, in particular NASA's Kepler and TESS exoplanet missions. You can search for the various data products for TESS on MAST using the various Lightkurve functions for Full Frame Images, Target Pixel Files, or Light Files for Specific Objects.

<https://github.com/lightkurve/lightkurve/blob/48b406a2133267fc03f09d115ecd5cd95a35c702/src/lightkurve/search.py#L723>