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FLARES ON SOLAR-TYPE STARS

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ABSTRACT

We present a statistical study of flares on solar-type stars based on TESS (Transiting Exoplanet Survey Satellite) observations. We used a two-minute cadence data obtained from sectors 1 to 37. Our software allows us to identify flares and determine its parameters such as: amplitude, duration, growth and decay times. Furthermore, we estimate the maximum luminosity and total energy of flares in two different methods. In the first two years of TESS observations, we already identified about 13000 flares from more than 3000 solar-type flaring stars. Based on flare energy distribution, we conclude that its energies range from 10^{31} to 10^{36} erg, with an average energy of 10^{34} erg.

SOLAR-TYPE STARS

Our sample of flaring solar-type stars observed by TESS counted over 3000 objects. We use effective temperature and surface gravity as criteria to select stars (Shibayama et al. (2013)). Effective temperatures range from 5100 K to 6000 K. The $log(g)$ had to be greater than 4.0. We obtain stellar parameters from MAST or SIMBAD databases if possible. Most of the stars selected for analysis (75%) were classified as spectral type G stars, 20% as K type, 4% as F and less than 1% as M. In total, more than 13000 flares have been detected.

METHODS OF FLARES DETECTION

For finding flares from TESS data we prepared an automated, three step software WARPFINDER (Wroclaw AlgoRithm Prepared For detectINg anD analysing stEllar flaRes). The first step is trend method based on consecutive de-trending of the light curves. Then we determine the standard deviation and check which data outliers points above the assumed sigma level. These detections are saved as potential stellar flares. This idea was taken from a paper by Davenport et al. (2014). The second step is the difference method. It is based on checking the flux difference between two consecutive points and examining the standard deviation. We define all points with a value greater than 3σ as a potential flare detection. The difference method was inspired by Shibayama et al. (2013). The events times of both methods are compared and the prepared list of potential stellar flares are then verified by the third method. We fit the assumed flare profiles to the observational data and check its quality with chi-square statistic. To distinguish a stellar flare from data noise we use the probability density function of F-distribution. Additional methods to reject false detections are the calculation of the flare profile skewness and the sector method. Moreover, we assume that a stellar flare should have a shorter rise time than its decline. We also reject all events with a duration of less than 6 observational points (12 minutes).

RESULTS

We identified 3292 flaring solar-type stars from all 307281 stars from TESS sectors 1-37. On these stars we detected 13273 flares. The star with the biggest number of detected flares (402) is TIC364588501 (HD 39150) observed in 23 sectors.

The Figure 1 shows the distributions of the basic parameters of stellar flares on solar-type stars: amplitudes, growth and decay times. The most of amplitudes do not exceed the value of 0.2 of the normalized flux with subtracted background. The duration of a stellar flares ranges from a few minutes to several hours, most often around 30-40 minutes. All events lasting less than 12 minutes were rejected. The average values of the growth times are much shorter than the decay times and are usually below 20 minutes. Most of the flares have decay times of several dozen minutes, although the longest are up to 500 minutes.

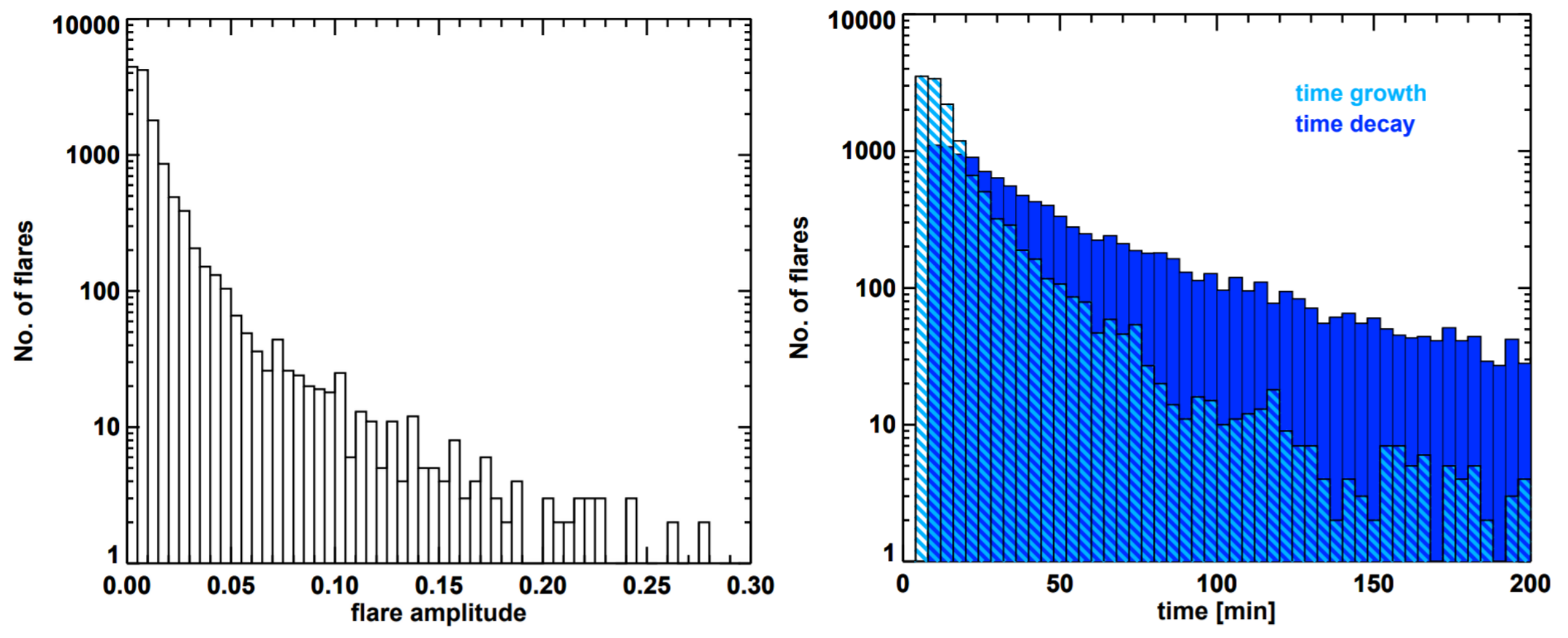

Figure 1: The distributions of the basic parameters of stellar flares: amplitude ($left$), growth and decay times ($right$).

The Figure 2 shows some of the distributions of the basic parameters of flaring solar-type stars: effective temperature, spectral type, mass and TESS magnitude. All stars form sectors 1 to 37 are marked in gray, and flaring solar-type stars are marked in dark blue. The temperature distribution is shown in the range of 5100 K to 6000 K due to assumptions for a solar-type star. This distribution is almost constant. On the right, there is also a division into the sub-types of G main-sequence stars. The masses of flaring stars are usually less than 1.1 times the mass of the Sun, which is the result of the assumed analysis of solar-type stars. The TESS magnitude distribution ranges from 2 mag to 17 mag. It is similar to the distribution for all stars observed in 37 sectors.

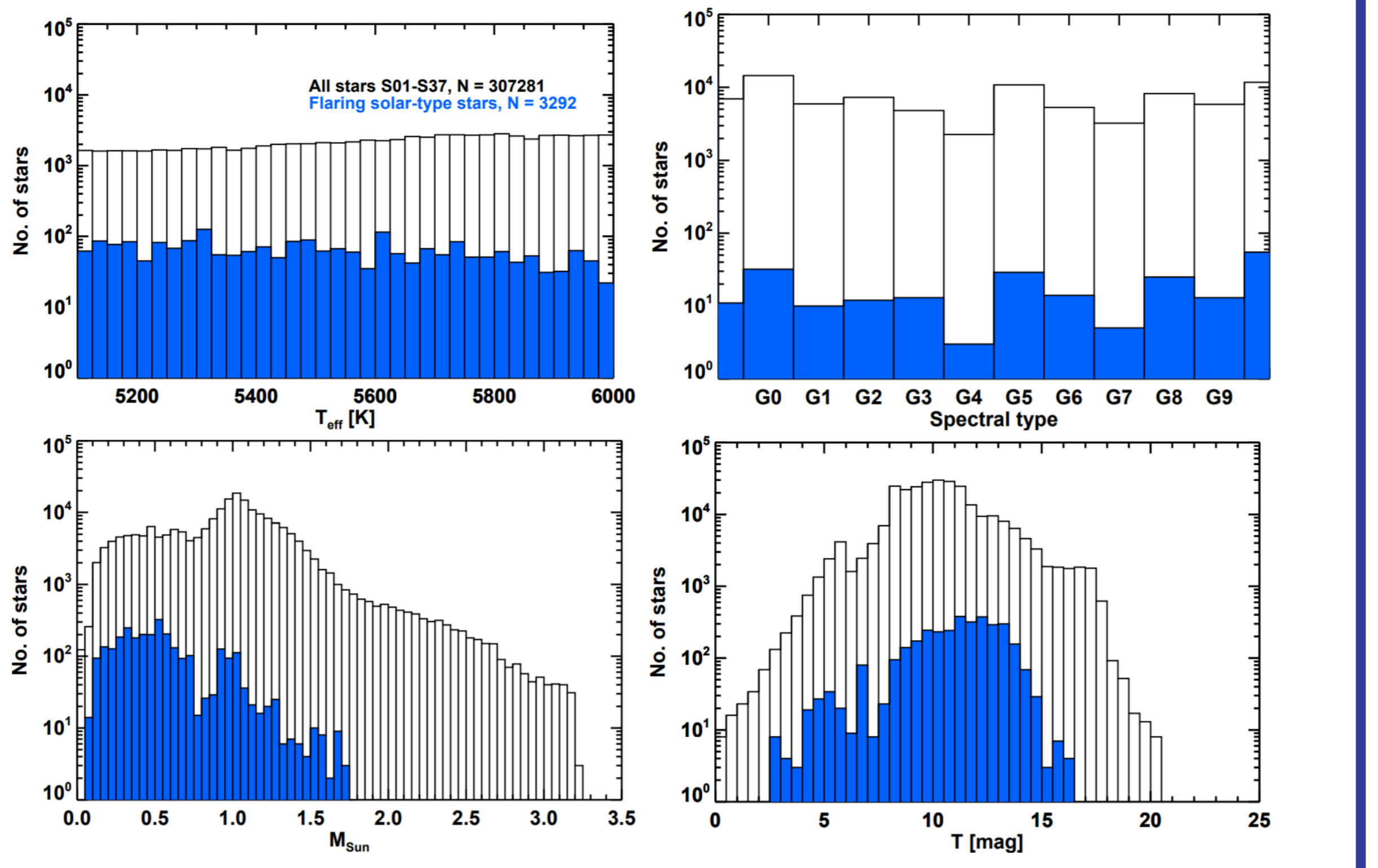

Figure 2: Histograms of the number of flaring stars (dark blue) compared with the total number of stars shown as a function of the stellar effective temperature ($top, left$), spectral type ($top, right$), mass ($bottom, left$) and TESS magnitude ($bottom, right$).

FLARE ENERGIES

Our software estimates the total energy of flares in two different methods. In the first one we assume black body radiation and effective temperature of a flare (T_{flare}) about 10000 K (Mochnacki & Zirin (1980); Hawley & Fisher (1992); Shibayama et al. (2013)). The bolometric flare luminosity (L_{flare}) and energy (E_{flare}) could then be calculated from:

$$L_{flare} = \sigma_{SB} T_{flare}^4 A_{flare} \tag{1}$$

$$E_{flare} = \int_{flare} L_{flare}(t) dt \tag{2}$$

The flare area (A_{flare}) is a function of flare amplitude, stellar radius, TESS response function and Planck function.
The second one is the method proposed by Kovari et al. (2007). In the first step we estimate the relative flare energy $\varepsilon_{\text{TESS}}$ by integrating the normalized flare intensity I_{norm} during the flare event:

$$\varepsilon_{\text{TESS}} = \int_{t1}^{t2} I_{\text{norm}} dt \tag{3}$$

Then we calculate flux of the star F_{star} using the spectrum of star $F(\lambda)$ taken from ATLAS9 (Castelli & Kurucz (2003)). Stellar radius R, $\log(g)$, T_{eff} and TESS response function $S_{\text{TESS}}(\lambda)$ are required in this method:

$$F_{\text{star}} = \int_{\lambda_1}^{\lambda_2} 4\pi R^2 F(\lambda) S_{\text{TESS}}(\lambda) d\lambda \tag{4}$$

Finally we estimate the flare energy E_{flare} from stars flux F_{star} in selected interval of wavelengths and relative flare energy $\varepsilon_{\text{TESS}}$:

$$E_{\text{flare}} = F_{\text{star}} \cdot \varepsilon_{\text{TESS}} \tag{5}$$

The Figure 3 shows the histograms of flares energies within solar-type stars from our analysis. Energy calculated using method based on Shibayama et al. (2013) is marked in dark blue (Energy v1) and based on Kovari et al. (2007) with light blue (Energy v2). The results of both methods differ from each other. The method using the spectrum of star usually gives higher energy estimation. The energies of stellar flares ranges from 10^{31} to 10^{36} erg, with an average about 10^{34} erg. Figure 4 shows the distributions of the flare energies from our sample of stars from sectors S01-S13 and from Doyle et al. (2020) (colored orange). The results obtained using stellar spectra are in very good agreement with Doyle et al. (2020).

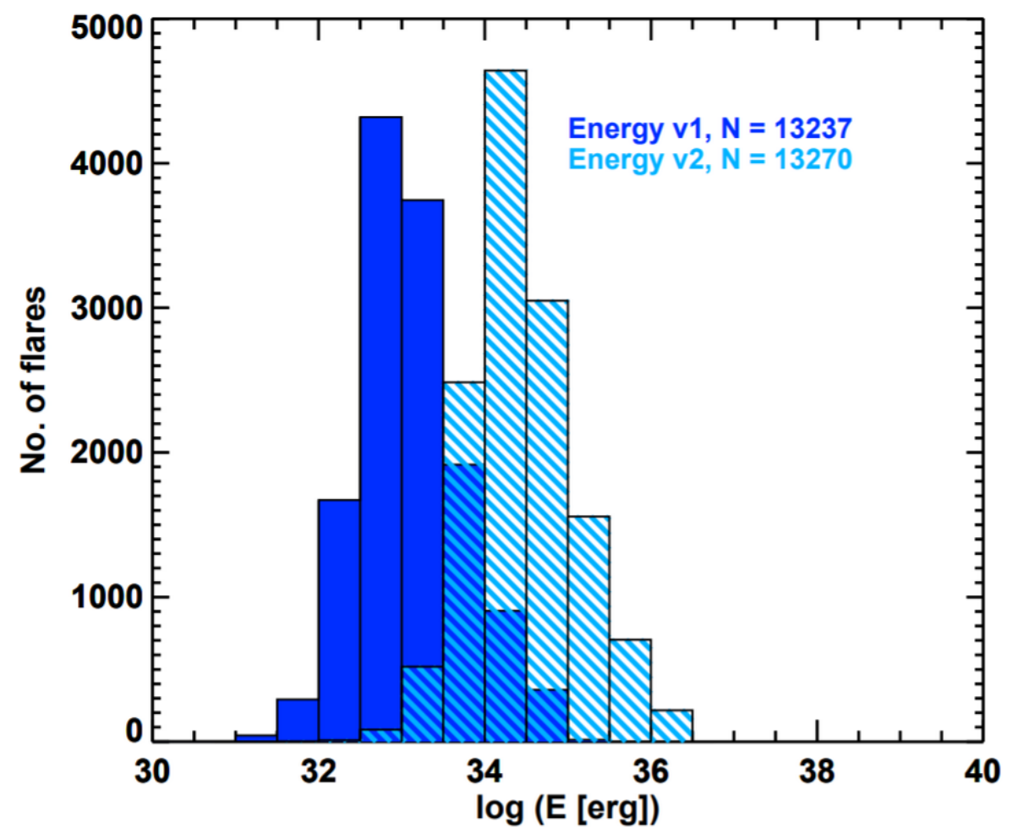

Figure 3: The distribution of flare energies for 3292 solar-type stars from S01-S37 estimated using methods based on Shibayama et al. (2013) (v1, dark blue) and based on Kovari et al. (2007) (v2, light blue).

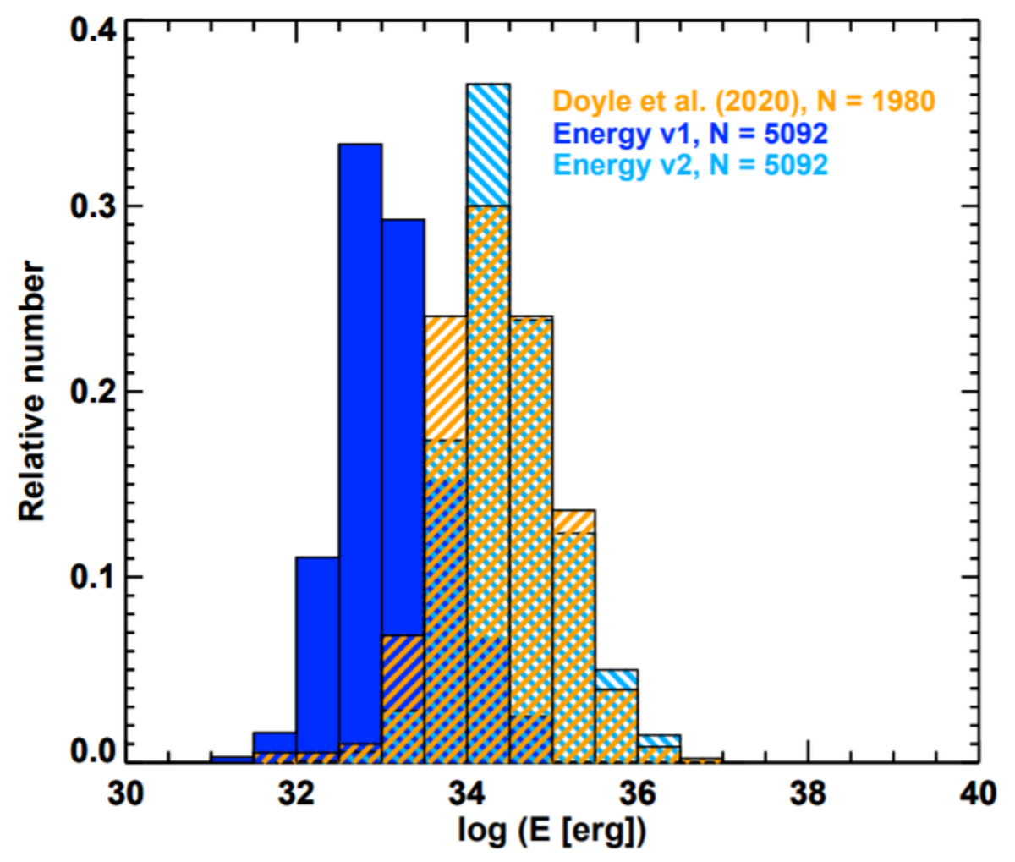

Figure 4: The distribution of flare energies for 1244 solar-type stars from S01-S13 estimated using both methods and the comparison with Doyle et al. (2020) (orange).

The Table 1 presents information about three solar-type stars with the flares of the highest energies found by our software. The energies was estimated using method based on Shibayama et al. (2013) (Energy v1) and Kovari et al. (2007) (Energy v2). The most energetic events have energy of approximately 10^{36} erg. It is in agreement with previous papers on this topic (Maehara et al. (2012), Tu et al. (2021)). We limited our analysis only to stars with radius smaller than 2 $R_\odot$ due to overvaluation of flares energy for stars with too large estimated radius values. Assuming that the bolometric energy of 10^{33} erg correspond to an X100 flare (Benz (2016)), detected events are more than X100000 flares.

Table 1. Table of the solar-type stars with the flares of the highest energies

TIC	Name	Energy v1 [erg]	Energy v2 [erg]	T_{eff} [K]	Mass [$M_\odot$]	Radius [$R_\odot$]
TIC175305230	Cl* NGC 2451 AR 52	9.07e+35	2.12e+36	5419	0.94	1.1
TIC420137030	TYC 4456-307-1	8.06e+35	1.86e+36	5935	1.08	1.1
TIC79358659	HD 321958	7.65e+35	1.84e+36	5626	1.0	1.3

Studies for solar-type stars have shown the occurrence of super flares with energies about 10000 times greater than the largest solar flares (Shibayama et al. (2013)). The appearance of such a strong flare in the Sun can lead to a magnetic storm on the Earth and wide spread blackout.

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