Blackbody Temperature of 200+ Stellar Flares Observed with the CoRoT Satellite

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Abstract

We estimated blackbody temperature for 209 flares observed at 69 F–K stars, significantly increasing the number of flare temperature determinations. We used the Blue and Red channels obtained by the 27 cm telescope of the CoRoT satellite at high cadence and long duration. The wavelength limits of the channels were estimated using spectra from the Pickles library for the spectral type and luminosity class of each star, provided by the Exodat Database. The temperatures were obtained from the flare energy Blue-to-Red ratio, using the flare equivalent duration and stellar flux in both channels. The expected value of the analyzed flares is equal to 6400 K with a standard deviation of 2800 K, where the mean stellar spectral type, weighted by the number of flares in each spectral subclass, is equal to G6. Contrary to our results, a stellar white-light flare is often assumed to emit as a blackbody with a temperature of 9000 or 10,000 K. Our estimates agree, however, with values obtained for solar flares. The GAIA G-band transmissivity is comparable to that of the CoRoT White channel, which allows us to calibrate the flares to the Gaia photometric system. The energy in the G band of the analyzed flares varies between $10^{32}$ and $10^{37}$ erg, and the flare area ranges from 30 $\mu$m to 3 sh (solar hemisphere). The energy release per area in a flare is proportional to $T_{\text{flare}}^4$, at least up to 10,000 K.

Unified Astronomy Thesaurus concepts: Stellar flares (1603); Optical flares (1166); Astrostatistics (1882); Artificial satellites (68); Stellar rotation (1629); Stellar properties (1624)

Supporting material: machine-readable tables

1. Introduction

Although solar flares are more noticeable in UV and X-ray observations, they emit in a broad range of electromagnetic radiation. In fact, most of the radiated flare energy emerges at visible and UV wavelengths (Woods et al. 2006; Kretzschmar 2011). Flares observed in the visible spectrum are called white-light flares (WLFs). Solar WLFs are generally rare events to observe, mainly due to the low contrast with the solar disk (Lin & Hudson 1976; Jess et al. 2008).

High-cadence, high-precision continuous photometry observations from space (e.g., Convection, Rotation and planetary Transits (CoRoT), Kepler, TESS) have made possible extensive observations of stellar flares in the visible on various types of stars. These stellar flares can be up to ~10,000 (or even a million; see Schaefer et al. 2000) times larger than the largest solar flares. Despite this, several statistical studies show that stellar flares have solar-like properties, indicating that they may also be the result of magnetic reconnection events (Namekata et al. 2017, and references within). Fast-rotating stars have higher magnetic activity, as is to be expected from the dynamo theory of magnetic field generation. In fact, it is observed that they have a higher occurrence rate of flares than slow rotators (Shibayama et al. 2013) but not more energetic flares (Maehara et al. 2012). Notsu et al. (2013) found that there is a correlation between spot coverage and flare energy.

Determining the flare temperature provides valuable information that can help us to understand the physical processes responsible for the flare emission (e.g., Kowalski et al. 2016). Unfortunately, these space missions only provide information in a single filter passband, not allowing us to estimate the temperature of the flare. There are some papers where it was estimated. Hawley & Fisher (1992) analyzed a large flare at the M-dwarf star AD Leo. They obtained a blackbody temperature of 8500—9500 K fitting the average surface flux observed at six passbands (Johnson U, B, V, and R and two in the near-UV) during the flare. Hawley et al. (2003) analyzed four other flares on AD Leo and obtained similar results (~9000 K). Kowalski et al. (2013) analyzed 20 flares in five M-dwarf stars using high-cadence near-UV and visible spectra. They observed that all flares present a linear decrease in flux at wavelengths from 4000 to 4800 Å, corresponding to a blackbody temperature between 9000 and 14,000 K. They reported variations in the Balmer jump during the flare that indicate an additional component to the blackbody emission in the near-UV range (Kowalski et al. 2019). Howard et al. (2020) used simultaneous observations in the narrow $g'$-band obtained by a series of small telescopes (Law et al. 2016; Evryscape) and the broadband filter of NASA’s TESS satellite (Ricker 2014) to estimate the temperature and energy of 47 flares on 27 K5–M5 dwarfs. They found that nearly half of the flares emit above 14,000 K during their peak. However, the temperature of the entire flare varies widely, from 2600 to 50,000 K.

Based on these stellar temperature estimations, the WLF spectrum is often described as a blackbody with a temperature between 9000 and 10,000 K and used to estimate the bolometric energy of the flare (e.g., Maehara et al. 2012, 2021; Shibayama et al. 2013; Davenport et al. 2020; Günther et al. 2020). A change in the assumed flare temperature may significantly affect the energy–frequency distribution estimate, which is used to model the atmospheric conditions of the...
planets orbiting the flaring star. This allows us to assess the possibility of life and the probability of becoming a candidate for a biosignature survey (e.g., Günther et al. 2020).

For solar WLs, there is an earlier estimation of a temperature similar to that of the M-dwarf stellar flares, $\sim9000$ K by Kretzschmar (2011). Later, Kerr & Fletcher (2014) estimated temperatures between 5000 and 6000 K, Kleint et al. (2016) between $\sim6000$ and 6300 K, and Namekata et al. (2017) between 5500 and 7000 K.

In this work, we used the CoRoT color channels to estimate the temperature of more than 200 stellar flares observed in more than 50 stars with different spectral types. We describe in Section 2 the data used and the fitting and equivalent duration estimation of the flares. Section 3 presents the estimation of the limits of the CoRoT color channels that we used in the flare temperature calculation, described in Section 4. As stellar rotation has an effect on stellar activity, the rotation estimate is presented in Section 5, to be compared with the flare temperatures. Finally, in Section 6, we took advantage of the similarity of the CoRoT White channel to the Gaia $G$ band to calibrate the analyzed flares into the Gaia photometric system. In Section 7, we present our conclusions.

2. Data and Methodology

CoRoT was a space-based mission that obtained precise photometric observations of hundreds of thousands of stars from 2007 to 2012 in two regions of the sky (one toward the Galactic center and another toward the Galactic anticenter; Baglin & CoRot Team 2016). We studied stars observed through the so-called Faint Stars or Exoplanet channel (Ollivier et al. 2016). The stellar images were dispersed by a prism that was in the optical path before the CCDs, producing a low-dispersion spectrum of each star. For about 6000 stars, CoRoT provided not only a light curve integrating the entire photometric mask (called White light curve) but also three light curves dividing the mask into three regions corresponding to different spectral bands whose fluxes were recorded separately (Auvergne et al. 2009). The boundaries within the mask were chosen so that each light flux was close to a given fraction of the total flux and corresponds to an integer number of columns on the CCD as the dispersion was done in rows (Figures 10 and 11 in Léger et al. 2009). These color light curves were named Red, Green, and Blue, although its spectral content varies with the shape of the photometric mask used, the star’s apparent magnitude, spectral type, etc. (Bordé et al. 2010). The flux in the Green channel is low compared to the others (Borsa & Poretti 2013) and was not used here owing to its low signal-to-noise ratio.

Drabent (2012) published a list of 111 flaring stars after analyzing all CoRoT light curves observed until 2010 December (including observational sequence LRA04). We used the light curves for these stars provided by the CoRoT public archive. Three data correction levels for each light curve are provided. We used the most basic (provided by the BAR extension in the FITS files), which does not include correction of jumps or replacement of invalid and missing data (Chaintreuil et al. 2016), as a flare could be misinterpreted as a jump or invalid data. The housekeeping temperature data show jumps (Ollivier et al. 2016) that can affect the light curve and mimic a flare. Thus, we disregard the corresponding time intervals in the analyzed light curves (provided by the keyword “statusfil” in the BARFILL extension$^3$). Although CoRoT observations last 32 s, in most stars, 16 observations are gathered at a cadence of 512 s (Ollivier et al. 2016). Approximately one-third of the analyzed stars have a cadence of 512 s, and the remaining have a cadence of 32 s.

We visually inspected each light curve and manually selected the approximate beginning and end of each flare, using FBEYE software developed by Davenport et al. (2014). We fitted each flare and its background using a two-exponential function plus a straight line:

$$F_{\text{local}}(t) = F_{\text{bk}}(t) + F_{\text{flare}}(t)$$

$$= a_4 + a_5 t + a_0 \left( e^{a_2(t-a_1)}, t < a_1 \right)$$

$$e^{-a_2(t-a_1)}, t \geq a_1$$

(1)

observed in each color channel. We applied a least-squares Levenberg–Marquardt minimization algorithm to obtain the best-fit flare parameters and a maximum likelihood via Markov Chain Monte Carlo algorithm (Foreman-Mackey et al. 2013) to estimate the uncertainties of the fitted parameters, using the LMFIT Python package. Figure 1 shows a few examples of the fitting. The flare fitted parameters are the flare peak flux ($a_0$), the peak flare occurrence time ($a_1$), the exponential growth rate ($a_2$), and the decay rate ($a_3$).

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$^3$ http://idoc-corot.iias.u-psud.fr

$^4$ See Table 24.15 in Chaintreuil et al. (2016) for a description.
The equivalent duration (ED) of a flare (Gershberg 1972) is given by

$$\text{ED} = \int_{0}^{\infty} \frac{F_{\text{flare}}(t)}{F_{\text{qu}}(t)} dt = \frac{a_{0}}{F_{\text{qu}}(t)} \left( \frac{1}{a_{2}} + \frac{1}{a_{3}} \right),$$

where $F_{\text{flare}}(t)$ is the flux due to only the flare (after removing the background) and $F_{\text{qu}}(t)$ is the flux in the quiescent state. As the background varies throughout the flare, we used the background value at the flare peak as the quiescent flux: $F_{\text{qu}} = a_{4} + a_{5} a_{3}$. Figure 2 shows the ED obtained for each flare observed in the Blue and Red channels. Only flares for which we obtained an ED greater than 1.5σ (where σ is the uncertainty in ED) were used here and are shown in the figure. The ED varies from 2 to 3000 s. There are 209 flares observed in both the Blue and Red channels and a similar number of flares that are visible only in the Red or Blue channel. The mean value of the Blue-to-Red ED ratio and its standard error is equal to 2.36 ± 0.09 (shown as a green line in Figure 2).

The flare peak flux ($a_{0}$ in Equation (1)) divided by the flux in the quiet state observed in the Blue channel versus in the Red channel is shown in Figure 3. The mean and its standard error of the Blue-to-Red flare peak amplitude ratio normalized by its respective quiet state is equal to 2.75 ± 0.09 (shown as a green line in Figure 3). The Blue-to-Red FWHM ratio is close to 1. The flare FWHM ranges from 2 minutes to 2.5 hr.

In our analysis, besides ruling out several flares where the ED was not well determined (i.e., ED < 1.5σ) owing to its small duration or amplitude, we also discarded those within a thermal jump or with missing data during the flare. In the end, we accepted 209 flares observed in both the Blue and Red channels. These flares belong to 69 stars, reducing the number of stars in our initial sample.

3. Blue and Red Channel Wavelength Limits

To obtain the chromatic light curves, the observed low-resolution stellar spectrum multiplied by the CoRoT response function was divided into three parts: the Blue band corresponds to the shorter wavelengths, the Red band to the longer ones, and the Green band to intermediate values. Unfortunately, the boundaries that separate the channels vary for each observed star and for each observation period (since the star may be on a different CCD; Bordé et al. 2010). In this section, we estimate these limits for each light curve: the upper wavelength limit of the Blue channel, $\lambda_{\text{Blue}}$, and the lower wavelength limit of the Red channel, $\lambda_{\text{Red}}$.

For each star, the spectral type and luminosity class were retrieved from the Exodat Database (Deleuil et al. 2009), later shown in Table 2. The stellar classification in the Exodat Database was estimated by fitting the apparent magnitude of CoRoT stars (obtained by ground-based multicolor broadband photometric observations) to the spectral flux from the Pickles Stellar Spectral Flux Library (Pickles 1998). Damiani et al. (2016) reported that the luminosity class is estimated with great significance and that the typical uncertainty on the spectral type is of half a spectral class. We used the spectra from the Pickles Library for the spectral type and luminosity class of the star $s$, $f_{\text{p}}(\lambda)$, to estimate the wavelength limits:

$$F_{\text{obs}}^{\text{Blue}}(l) = \int_{0}^{\lambda_{\text{blue}}(l,s)} \Phi(\lambda)f_{\text{p}}(\lambda) \lambda d\lambda,$$

$$F_{\text{obs}}^{\text{White}}(l) = \int_{0}^{\infty} \Phi(\lambda)f_{\text{p}}(\lambda) \lambda d\lambda,$$

$$F_{\text{obs}}^{\text{Red}}(l) = \int_{\lambda_{\text{red}}(l,s)}^{\infty} \Phi(\lambda)f_{\text{p}}(\lambda) \lambda d\lambda,$$

where the terms on the left-hand side are the observed average stellar flux ratios for each light curve $l$. $\Phi(\lambda)$ is the CoRoT Response Function for the Faint Stars channel (Auvergne et al. 2009). Most stars $s$ have only one light curve $l$, except for eight of them, which have two light curves observed 4 yr apart. We used the Pickles library UVKLIB, which covers the spectral range 1150–25000 Å. In the library, the fluxes are in units of erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, and the original fluxes in the Pickles $V$ band were normalized to a 0 mag in the Vega magnitude system. As

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5 http://cesam.lam.fr/exodat
6 https://archive.stsci.edu/hlsp/reference-atlasses/cdbs/pickles/dat_uvk/
7 https://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/astronomical-catalogs/pickles-atlas
the functions on the right-hand side of Equation (3) vary smoothly with \( \lambda_{\text{Blue}}(l, s) \) and \( \lambda_{\text{Red}}(l, s) \), we can use the error propagation equation (Bevington & Robinson 2003). The uncertainties of the wavelength limits, \( \epsilon_{\lambda_{\text{Blue}}}(l, s) \) and \( \epsilon_{\lambda_{\text{Red}}}(l, s) \), were estimated dividing the standard error of the mean observed flux ratio by the derivative of the right-hand side expression at the estimated wavelength limit. The uncertainties are very small, less than 0.2 Å.

We also included the uncertainty in the stellar classification in the wavelength limit estimation. To be on the safe side, we assumed twice the uncertainty in stellar classification given in Damiani et al. (2016). For each light curve \( l \), we estimated the limit of each channel, using all spectra in the Pickles library within plus/minus a spectral class and within plus/minus two luminosity classes of the star \( s \): \( \lambda_{\text{Blue}}(l) = (\lambda_{\text{Blue}} \pm \epsilon_{\lambda_{\text{Blue}}}(l, s)) \) and \( \lambda_{\text{Red}}(l) = (\lambda_{\text{Red}} \pm \epsilon_{\lambda_{\text{Red}}}(l, s)) \), for our stars, there are between 18 and 68 spectra within these uncertainties (18 \( \leq N \leq 68 \)), and only 7 of the 69 stars have less than 30 spectra. Next, we calculated the weighted average limit of the channels for each light curve \( l \), \( \lambda_{\text{Blue}}(l) \) and \( \lambda_{\text{Red}}(l) \), where the weight is given by the inverse square of the uncertainty. We estimated the uncertainty in the weighted averages (Bevington & Robinson 2003 and in more detail in the supplement of Kirchner & Allen 2020): \( \sigma_{\lambda_{\text{Blue}}}(l) \) and \( \sigma_{\lambda_{\text{Red}}}(l) \). They have a percent uncertainty ranging from 2% to 5%. The results are shown in Figure 4 (top panel). Later in this paper, we compare our results using these limits (Figure 4) with limits calculated as described above, but assuming a smaller uncertainty in stellar classification: within plus/minus half a spectral class and within plus/minus one luminosity class. These weighted average limits agree with the previous ones within their uncertainty. As expected, their uncertainties are half of the former ones.

According to Rouan et al. (1999), the fraction in each channel should not be far from 20% of the bluest photons for the Blue channel and 65% of the reddest photons for the Red channel. The averages over the analyzed stars of the Blue-to-White and Red-to-White observed flux ratio, measured in electrons, are equal to 0.16 \( \pm 0.01 \) and 0.72 \( \pm 0.01 \), respectively, where the uncertainties are given by the error of the mean. However, if we calculate the stellar fluxes in units of energy using the right-hand side of Equations (3), then without multiplying by the wavelength, the average ratios are 0.22 \( \pm 0.01 \) and 0.63 \( \pm 0.01 \), respectively, which agree with the fractions given by Rouan et al. (1999).

4. Effective Flare Temperatures

We assumed that the spectrum of WLFs can be described by a blackbody, \( B_\nu \), with temperature, \( T_\text{flare} \) (Mohnczaki & Zirin 1980; Shibayama et al. 2013; Günther et al. 2020, and others). Following Shibayama et al. (2013), we can estimate the flare luminosity \( L_\text{flare} \) observed by CoRoT in the White channel, in photons, as

\[
L_\text{flare}(t) = A_\text{flare}(t) \int_0^\infty \Phi(\lambda) B_\nu(T_\text{flare}) \lambda d\lambda,
\]

where \( A_\text{flare}(t) \) is the area of the flare as a function of time and \( \Phi(\lambda) \) is the CoRoT Response Function for the Faint Stars channel (Figure 4).

The ED (Equation (2)) can be written as

\[
ED = \frac{1}{L_*} \int_{t_{\text{flare}}} L_\text{flare}(t) dt,
\]

where \( L_* \) is the luminosity of the star observed with the CoRoT White channel. Assuming that the flare area and temperature are constant during the flare (as in Shibayama et al. 2013; Günther et al. 2020) and substituting Equation (4) into Equation (5), we have

\[
ED = \frac{A_\text{flare}}{L_*} \Delta t \int_0^\infty \Phi(\lambda) B_\nu(T_\text{flare}) \lambda d\lambda,
\]

where \( \Delta t \) is the flare duration. The ratio between the EDs observed in the Blue and Red channels is

\[
\frac{ED_{\text{Blue}}}{ED_{\text{Red}}} = \frac{F_{\text{Red}} \Delta t_{\text{Red}}}{F_{\text{Blue}} \Delta t_{\text{Red}}} \int_{\lambda_{\text{Blue}}}^{\lambda_{\text{Red}}} \Phi(\lambda) B_\nu(T_\text{flare}) \lambda d\lambda.
\]

We also assumed that the area of the flare is the same in observations using the Blue or the Red channel. The energy of a flare, \( E \), is defined as the product of its ED and the quiescent luminosity of the star \( L_* \) (e.g., Shibayama et al. 2013; Hawley et al. 2014; Günther et al. 2020; Rodríguez Martínez et al. 2020). Using Equation (7), the energy ratio is...
given by

\[ \frac{E_{\text{Blue}}}{E_{\text{Red}}} = \frac{E_{\text{Blue}}}{E_{\text{Red}}} \frac{F_{\text{Blue}}}{F_{\text{Red}}} = \frac{\Delta T_{\text{Blue}}}{\Delta T_{\text{Red}}} \int_{\lambda_{\text{Blue}}}^{\lambda_{\text{Red}}} \Phi(\lambda) B_\lambda(T_{\text{blue}}(k)) \lambda d\lambda \int_{\lambda_{\text{Red}}}^{\lambda_{\text{Red}}} \Phi(\lambda) B_\lambda(T_{\text{red}}(k)) \lambda d\lambda. \] (8)

The flare duration was calculated using the flare fitted parameters (Equation (1)). The analyzed flares have, on average, the same duration in the Blue and Red channels. We used Equation (8) to estimate \( T_{\text{flare}}(k) \), for each flare \( k \) observed in a given light curve \( l \), since it is the only unknown parameter in the equation:

\[ \frac{E_{\text{Blue}}(l, k)}{E_{\text{Red}}(l, k)} = \frac{E_{\text{Blue}}(l, k)}{E_{\text{Red}}(l, k)} \frac{F_{\text{obs}}(l, k)}{F_{\text{obs}}(l, k)} = \frac{\int_{\lambda_{\text{Blue}}(l)}^{\lambda_{\text{Red}}(l)} \Phi(\lambda) B_\lambda(T_{\text{flare}}(k)) \lambda d\lambda}{\int_{\lambda_{\text{Red}}(l)}^{\lambda_{\text{Red}}(l)} \Phi(\lambda) B_\lambda(T_{\text{flare}}(k)) \lambda d\lambda}. \] (9)

The flare energy ratio as a function of \( T_{\text{flare}} \), given by the ratio of integrals on the right-hand side of Equation (9), is shown in Figure 5. It varies smoothly with \( T_{\text{flare}} \) for a given pair of wavelength limits: \( \lambda_{\text{Blue}}(l) \) and \( \lambda_{\text{Red}}(l) \). Using the error propagation equation, we estimated the flare temperature uncertainty, \( \sigma_{T_{\text{flare}}}(k) \), by dividing the uncertainty of the observed flare energy ratio, \( E_{\text{Blue}}/E_{\text{Red}}(k) \cdot F_{\text{Blue}}/F_{\text{Red}}(l) \), by the derivative of the right-hand side expression at the estimated flare temperature. As seen in Figure 5, the slope of the flare energy rate tends to zero as the flare temperature increases. Therefore, the estimated uncertainty in the flare temperature increases with the flare temperature. This is a consequence of using observations in the visible range to estimate high temperatures. According to Wien’s law, a blackbody with a temperature of 10,000 K will have its maximum emission at 2900 Å and outside the CoRoT Response Function (Figure 4).

To take into account the uncertainty in the estimated wavelength limits, we added noise to the flare temperature calculation. For each pair \( \lambda_{\text{Blue}}(k) \) and \( \lambda_{\text{Red}}(k) \), we generated 1000 input pairs by adding different random realizations of Gaussian noise with a standard deviation given by \( \sigma_{\text{noise}}(l) \) and \( \sigma_{\text{noise}}(l) \), respectively. The final estimate of the flare temperature is the weighted average of 1000 estimates obtained using perturbed input wavelength limits: \( (T_{\text{flare}} \pm \sigma_{\text{noise}})(k) \) (Table 2). The percent uncertainty of the weighted mean ranges from 10% to 40%. Figure 6 (first row) shows the average flare temperatures for each star (in the same color) in ascending order of the average temperature of the flares in a given star. A total of 70% of the analyzed stars have only one or two flares. Those with two or more flares often have similar flare temperatures. Figure 7 shows the temperatures for stars with six or more flares.

We checked whether there is any dependence of the flare temperature with stellar spectral type. Figure 6 (second row) shows the flare temperatures in intervals of half-spectral type, where within each interval the temperatures are in ascending order and the flares in each luminosity class are in a different color. We calculated the weighted average of the flare temperature over each interval, which is shown in the third row. The average over all luminosity classes is shown in black. The average flare temperature, including all luminosity classes (black circles), ranges from 4700 ± 1300 K for spectral type K4 to 9600 ± 3500 K for F5 type, and the slope of the linear regression is equal to 1800 ± 1400 K per spectral type. The Pearson correlation coefficient (of the black circles) is 0.9, which has only a 5% probability of not being correlated (Bevington & Robinson 2003). We calculated the correlation coefficient after adding normally distributed random numbers with the same standard deviation of the mean flare temperature (shown in the third row) to examine the effect of their uncertainty on the correlation. The average Pearson coefficient and its standard deviation of 10,000 instances is 0.58 ± 0.37, and the probability of not being correlated is 30%.

Next, we analyzed the frequency distribution of the estimated flare temperatures. Figure 8 shows the histogram (solid black line) of the 209 \( T_{\text{flare}}(k) \) plotted in Figure 6 (first row). We estimated the probability density function (pdf) using the kernel density estimator (KDE) method (Silverman 1986)—with a Gaussian kernel—without taking into account flare temperature uncertainties. It agrees well with the histogram after the pdf was multiplied by the number of flares and the size of the histogram bin (solid red line). The kernel has an optimal window width (given by Equations (3.30) and (3.31) in Silverman 1986) equal to 983 K, which is used as the histogram bin width (solid black line). However, when including the flare temperature uncertainties in the estimation, the normalized pdf (blue line) has its maximum shifted toward a smaller flare temperature, with a mode equal to 5300 K. The distribution no longer has a long tail, and the width of the highest density interval (HDI) is narrower by 33%. This is to be expected, since flares with high temperatures have greater uncertainties, as mentioned earlier. In Table 1, we summarize the characteristics of the distributions (called “A”). They give us some indication of the upper and lower limits of the flare temperature distribution. The average spectral type of all flaring stars, weighted by the number of flares observed in stars in each spectral subclass, is equal to G6.
As mentioned in Section 3, we also calculated wavelength limits using a smaller uncertainty in the stellar classification (i.e., within plus/minus half a spectral class and within plus/minus one luminosity class). Reestimating \( T_{\text{flare}} \) in the same way as described above, but with these wavelength limits, we find that the new \( T_{\text{flare}} \) are systematically larger than before by a small amount, which is, on average, equal to \( 1 \sigma_{\text{flare}} \). Their histogram is shown in Figure 8 by a black dashed line. Their normalized pdf's calculated without including the uncertainties (dashed red line) and including the uncertainties (not shown in the figure) have modes and mean values that are a few percent larger than before (labeled “B” in Table 1).

We did a simple exercise to see how higher-than-observed flare temperatures would show in the results of our analysis. We artificially increased the value of the observed ED ratio given as input to Equation (9) to analyze the corresponding increase in \( T_{\text{flare}}(k) \). After increasing the ED ratio by 50% and 100% and repeating the calculation of \( T_{\text{flare}}(k) \) as described above, the estimated pdf is shifted by \( \sim 20\% \) (green solid line) and \( \sim 40\% \) (green dashed line) in \( T_{\text{flare}} \), respectively, while the width of 75% HDI increases by \( \sim 40\% \) and \( \sim 80\% \), respectively. A broad HDI width indicates a greater uncertainty in the parameter determination, which could be explained by the difficulty of observations in the visible range to measure large flare temperatures.

Figure 6. First row: weighted mean flare temperatures, \( T_{\text{flare}}(k) \), of the 209 flares and their standard deviation, \( \sigma_{\text{flare}}(k) \). The flares in a given star are shown in the same color. They are ordered with increasing mean temperature of all flares in a given star. Second row: same as the first row, but as function of spectral type, going from late- to early-type stars, in intervals of half a spectral class. The spectral type at the center of each interval is shown at the bottom of the panel. Inside each spectral class interval, the flare temperatures are in ascending order. The different colors are for the different luminosity classes. Third row: weighted average of the temperature of the flares vs. the average of the spectral subclass corresponding to the flares within each interval of half a spectral class. The averages for a given luminosity class, when there are four or more flares, are shown in different colors (as in the second row). The averages including all luminosity classes are shown in black, and their linear regression is given by the black dashed line. The vertical error bars correspond to the standard deviation of the flare temperature weighted average, and the horizontal error bars correspond to the standard deviation of the average of the spectral subclass. The absence of a horizontal bar means that only one spectral type was used in the temperature averaged.
5. Rotation

As suggested by dynamo theories and obtained from observations of cool stars, of any spectral type, the stellar activity increases with the rate of rotation and even more so with the Rossby Ro number, where small values of Ro indicate very active stars (Donati & Landstreet 2009). On the other hand, intermediate- and high-mass stars exhibit virtually no intrinsic variability. We calculated the stellar rotation to search for a correlation with flare temperature.

The presence of active regions on a star’s surface produces periodic variations in stellar observed brightness, due to the region’s motion relative to the observer as it follows the star’s rotation. However, other phenomena can also result in periodic variations in the light curve, such as eclipsing binaries, planetary transits, and pulsations. To distinguish them, we need not just a more detailed analysis but especially radial velocity measurements, both of which are outside the scope of this work. We analyzed the autocorrelation function (ACF) as described in McQuillan et al. (2013), after smoothing the White channel light curves using a 4 hr Gaussian filter (Table 2). When the light curve is longer than two rotation periods, several maxima of the ACF

Table 1

| Line   | Mode | Mean | σ  | Lower  | Upper  |
|--------|------|------|----|--------|--------|
| A      | yes  | blue | 5300 | 6400 | 2800 | 3400 | 8100 |
| B      | yes  | none | 5400 | 6600 | 2700 | 3500 | 8200 |
| A      | no   | red  | 5800 | 8400 | 4600 | 3300 | 10300 |
| B      | no   | −red | 6200 | 8700 | 4700 | 3700 | 10700 |
| 1.5×   | no   | green| 7200 | 10200 | 5000 | 3900 | 13600 |
| 2.0×   | no   | −green| 8400 | 12100 | 5700 | 4600 | 17300 |
| 1.5×   | yes  | none | 6300 | 7700 | 3600 | 3400 | 10000 |
| 2.0×   | yes  | none | 7100 | 9100 | 4500 | 3500 | 11900 |

Note. The table also shows for comparison the pdf properties of the results obtained assuming a smaller uncertainty in the stellar classification (Silverman 1986; using a Gaussian kernel) with and without taking into account flare temperature uncertainty. The pdf’s obtained with the kernel density estimation (Silverman 1986; using a Gaussian kernel) with and without taking into account flare temperature uncertainty are shown as blue and red lines, respectively. The histogram shown with a dashed black line is for mean flare temperatures obtained using wavelength limits estimated assuming a smaller uncertainty in the stellar classification used (i.e., half a spectral type and one luminosity class). It is slightly displaced horizontally for a better visualization. Its pdf estimate, without taking into account the uncertainty, is shown by the dashed red line. The green solid and dashed lines show the pdf (without taking into account flare temperature uncertainty) obtained by increasing the input ED by 50% and 100%, respectively. The pdf’s plotted here were normalized to be compared with the histograms; they were multiplied by the number of flares (209) and the size of the histogram bin (983 K).
Table 2
The Spectral Type, Rotation Period, Flare Temperature, Gaia Flare Energy, and Flare Area for the 69 Flaring Stars Analyzed

| CoRoT ID | Type | $P_{rot}$ (days) | $T_{flare}$ (1000 K) | $E_{flare}$ (erg) | $A_{flare}$ (cm$^2$) |
|----------|------|------------------|----------------------|-------------------|----------------------|
| 223941972 | A0IV | 4.90 ± 0.02 | 8.84 ± 0.83 | (33.4 ± 4.9) × 10$^{34}$ | (25.5 ± 3.0) × 10$^{19}$ |
| 224008170 | A5IV | 1.06 ± 0.01 | 6.44 ± 0.66 | (92.6 ± 6.9) × 10$^{33}$ | (25.7 ± 1.2) × 10$^{20}$ |
| 110685010 | F0III | 5.510 ± 0.007 | 18.9 ± 6.1 | (54.1 ± 9.5) × 10$^{32}$ | (57.6 ± 4.4) × 10$^{19}$ |
| 102326330 | F5III | 4.141 ± 0.001 | 9.1 ± 1.7 | (88.5 ± 2.5) × 10$^{33}$ | (45.1 ± 1.2) × 10$^{19}$ |
| 102332965 | F5III | 6.247 ± 0.006 | 8.2 ± 1.4 | (72.0 ± 2.4) × 10$^{33}$ | (49.5 ± 1.4) × 10$^{19}$ |
| 102948867 | F5III | 8.79 ± 0.01 | 17.2 ± 5.6 | (7.5 ± 1.3) × 10$^{33}$ | (30.7 ± 3.4) × 10$^{18}$ |
|           |       |                 | 9.1 ± 1.7 | (88.5 ± 2.5) × 10$^{33}$ | (45.1 ± 1.2) × 10$^{19}$ |
| 223940041 | F5III | 3.377 ± 0.006 | 10.4 ± 2.2 | (70.9 ± 2.7) × 10$^{33}$ | (32.7 ± 1.0) × 10$^{19}$ |
| 22984608 | F5III | 6.20 ± 0.02 | 10.0 ± 2.1 | (63.8 ± 2.3) × 10$^{34}$ | (226.9 ± 7.4) × 10$^{19}$ |
| 102925086 | F8I  | 13 ± 3 | 19.8 ± 8.1* | (17.1 ± 3.1) × 10$^{33}$ | (10.4 ± 1.0) × 10$^{19}$ |
| 110773079 | F8I  | 5.29 ± 0.05 | 9.9 ± 2.3 | (87.0 ± 8.2) × 10$^{32}$ | (109.6 ± 6.3) × 10$^{17}$ |
| 211607284 | F8IV | 2.013 ± 0.001 | 7.7 ± 1.1 | (7.4 ± 2.4) × 10$^{32}$ | (6.8 ± 2.2) × 10$^{17}$ |
| 221628176 | F8IV | 3.43 ± 0.03 | 6.71 ± 0.88 | (10.0 ± 3.7) × 10$^{34}$ | (3.5 ± 1.3) × 10$^{21}$ |
| 223959652 | F8IV | 3.636 ± 0.004 | 6.19 ± 0.70 | (79.2 ± 4.9) × 10$^{33}$ | (45.9 ± 1.9) × 10$^{20}$ |
| 223970694 | F8IV | 1.478 ± 0.002 | 7.8 ± 1.1 | (18.3 ± 4.4) × 10$^{33}$ | (13.9 ± 1.5) × 10$^{19}$ |
| 223983509 | G0III | 2.383 ± 0.003 | 8.0 ± 1.3 | (25.1 ± 2.1) × 10$^{34}$ | (28.5 ± 1.3) × 10$^{20}$ |
| 102895901 | G0III | 1.6236 ± 0.0004 | 8.3 ± 1.3 | (5.5 ± 1.5) × 10$^{34}$ | (20.6 ± 2.8) × 10$^{19}$ |
| 104228454 | G0III | 13.69 ± 0.02 | 4.37 ± 0.54 | (8.1 ± 1.0) × 10$^{35}$ | (97.0 ± 7.7) × 10$^{19}$ |
| 106054338 | G0III | 0.529 ± 0.001 | 6.60 ± 0.83 | (149.4 ± 8.4) × 10$^{32}$ | (39.5 ± 1.3) × 10$^{19}$ |
| 223980621 | G0V  | 3.1 ± 0.7 | 8.0 ± 1.2 | (48.5 ± 4.5) × 10$^{32}$ | (156.1 ± 8.2) × 10$^{18}$ |
| 102611863 | G0III | 47 ± 11 | 8.1 ± 1.7 | (18.0 ± 5.4) × 10$^{35}$ | (8.6 ± 2.4) × 10$^{21}$ |
| 102715243 | G0IV | 2.2460 ± 0.0004 | 10.9 ± 2.3 | (41.9 ± 4.3) × 10$^{33}$ | (80.8 ± 6.8) × 10$^{19}$ |
| 102859855 | G0IV | 8.13 ± 0.05 | 8.7 ± 1.5 | (64.9 ± 8.8) × 10$^{33}$ | (67.4 ± 6.6) × 10$^{18}$ |
| 110744899 | G0IV | 0.413 ± 0.001 | 8.7 ± 1.5 | (7.8 ± 1.0) × 10$^{33}$ | (46.3 ± 1.8) × 10$^{19}$ |
| 223980621 | G0V  | 3.1 ± 0.7 | 8.0 ± 1.2 | (48.5 ± 4.5) × 10$^{32}$ | (156.1 ± 8.2) × 10$^{18}$ |
| 105085606 | G2I  | 5.248 ± 0.007 | 8.7 ± 1.7 | (21.3 ± 2.1) × 10$^{32}$ | (37.2 ± 2.3) × 10$^{18}$ |
| 500007157 | G2I  | 4.34 ± 0.02 | 11.9 ± 2.9 | (14.3 ± 2.6) × 10$^{34}$ | (13.7 ± 2.2) × 10$^{20}$ |
| 223993277 | G2IV | 1.175 ± 0.003 | 4.23 ± 0.41 | (86.0 ± 7.6) × 10$^{33}$ | (84.3 ± 3.3) × 10$^{20}$ |
Table 2 (Continued)

| CoRoT ID   | Type | $P_{\text{rot}}$ (days) | $T_{\text{eff}}$ (1000 K) | $E_{\text{ej}}$ (erg) | $A_{\text{ej}}$ ($\text{cm}^2$) |
|------------|------|--------------------------|---------------------------|------------------------|---------------------------------|
| 102854684  | G2IV | 1.097 ± 0.003$^b$       | (13.9 ± 1.0) × 10$^{34}$ | (69.5 ± 3.5) × 10$^{36}$ |                                 |
| 604183778  | G2V  | 0.740 ± 0.003           | (24.6 ± 5.0) × 10$^{33}$ | (25.9 ± 2.4) × 10$^{36}$ |                                 |
| 102926046  | G2V  | 2.368 ± 0.004           | (164.2 ± 7.8) × 10$^{33}$ | (239.8 ± 8.2) × 10$^{36}$ |                                 |
| 221649345  | G2V  | 1.536 ± 0.006           | (70.3 ± 5.0) × 10$^{33}$ | (75.8 ± 3.1) × 10$^{36}$ |                                 |
| 223945488  | G2V  | 3.142 ± 0.004           | (246 ± 2.8) × 10$^{34}$  | (135.7 ± 8.2) × 10$^{36}$ |                                 |
| 315258285  | G2V  | 0.897 ± 0.002           | (10.4 ± 1.2) × 10$^{33}$ | (119.0 ± 7.4) × 10$^{36}$ |                                 |
| 102632674  | G5II | 6.07 ± 0.02             | (13.5 ± 3.3) × 10$^{32}$ | (19.2 ± 2.5) × 10$^{36}$ |                                 |
| 110680553  | G5II | 6.567 ± 0.002           | (37.1 ± 5.4) × 10$^{33}$ | (89.6 ± 7.0) × 10$^{36}$ |                                 |
| 104150155  | G5III| 6.867 ± 0.002           | (61.0 ± 9.3) × 10$^{34}$ | (57.1 ± 5.6) × 10$^{36}$ |                                 |
| 102615551  | G8III| 3.8771 ± 0.0004$^c$     | (11.5 ± 2.1) × 10$^{32}$ | (8.1 ± 1.2) × 10$^{36}$ |                                 |
| 110662866  | G8III| 2.959 ± 0.001           | (33.6 ± 5.2) × 10$^{32}$ | (37.1 ± 5.2) × 10$^{36}$ |                                 |
| 102590771  | G8V  | 3.71 ± 0.03             | (20.5 ± 3.7) × 10$^{32}$ | (40.7 ± 6.0) × 10$^{36}$ |                                 |
| 223961132  | G8V  | 3.829 ± 0.005$^d$       | (16.6 ± 2.6) × 10$^{32}$ | (39.9 ± 5.6) × 10$^{36}$ |                                 |
| 110681935  | K0III| 4.33 ± 0.10             | (20.2 ± 3.1) × 10$^{32}$ | (26.6 ± 3.8) × 10$^{36}$ |                                 |
| 110747714  | K0III| 4.775 ± 0.006           | (21.3 ± 3.1) × 10$^{32}$ | (25.3 ± 3.2) × 10$^{36}$ |                                 |
| 221647275  | K0III| 3.732 ± 0.001           | (4.9 ± 1.2) × 10$^{33}$  | (12.5 ± 2.3) × 10$^{36}$ |                                 |
| 102718810  | K0III| 1.86 ± 0.03$^h$         | (4.2 ± 1.3) × 10$^{34}$  | (10.6 ± 2.6) × 10$^{36}$ |                                 |
|            |      |                          | (45.9 ± 8.2) × 10$^{33}$ | (33.1 ± 4.8) × 10$^{36}$ |                                 |
|            |      |                          | (5.5 ± 1.9) × 10$^{34}$  | (4.2 ± 1.2) × 10$^{36}$ |                                 |
|            |      |                          | (30.8 ± 7.3) × 10$^{33}$ | (11.1 ± 1.5) × 10$^{36}$ |                                 |
|            |      |                          | (3.6 ± 1.3) × 10$^{34}$  | (4.0 ± 1.3) × 10$^{36}$ |                                 |
|            |      |                          | (18.5 ± 5.5) × 10$^{34}$ | (13.8 ± 3.5) × 10$^{36}$ |                                 |
|            |      |                          | (7.9 ± 1.1) × 10$^{34}$  | (33.0 ± 2.4) × 10$^{36}$ |                                 |
|            |      |                          | (34.5 ± 3.3) × 10$^{32}$ | (52.6 ± 3.6) × 10$^{36}$ |                                 |
|            |      |                          | (30.0 ± 1.8) × 10$^{32}$ | (21.9 ± 1.1) × 10$^{36}$ |                                 |
|            |      |                          | (34.5 ± 3.3) × 10$^{32}$ | (52.6 ± 3.6) × 10$^{36}$ |                                 |
|            |      |                          | (35.9 ± 1.6) × 10$^{32}$ | (72.6 ± 2.4) × 10$^{36}$ |                                 |
|            |      |                          | (29.9 ± 3.0) × 10$^{33}$ | (59.4 ± 3.0) × 10$^{36}$ |                                 |
|            |      |                          | (42.1 ± 4.4) × 10$^{32}$ | (88.0 ± 5.4) × 10$^{36}$ |                                 |
|            |      |                          | (31.4 ± 1.5) × 10$^{33}$ | (81.6 ± 3.1) × 10$^{36}$ |                                 |
|            |      |                          | (26.8 ± 1.2) × 10$^{33}$ | (43.5 ± 1.2) × 10$^{36}$ |                                 |
|            |      |                          | (60.4 ± 4.1) × 10$^{32}$ | (21.2 ± 1.0) × 10$^{36}$ |                                 |
|            |      |                          | (40.6 ± 7.1) × 10$^{32}$ | (17.9 ± 2.4) × 10$^{36}$ |                                 |
|            |      |                          | (28.9 ± 4.2) × 10$^{32}$ | (25.4 ± 2.9) × 10$^{36}$ |                                 |
|            |      |                          | (157.6 ± 9.5) × 10$^{32}$| (206.1 ± 7.6) × 10$^{36}$|                                 |
|            |      |                          | (44.4 ± 2.0) × 10$^{33}$ | (281.8 ± 9.4) × 10$^{36}$|                                 |
|            |      |                          | (101.1 ± 7.1) × 10$^{32}$| (18.8 ± 1.0) × 10$^{36}$ |                                 |
|            |      |                          | (43.6 ± 7.0) × 10$^{32}$ | (14.4 ± 1.0) × 10$^{36}$ |                                 |

Notes:
- $^a$ From 171 to 175 d
- $^b$ From 176 to 180 d
- $^c$ From 191 to 195 d
- $^d$ From 201 to 205 d
- $^e$ From 211 to 215 d
- $^f$ From 221 to 225 d
- $^g$ From 231 to 235 d
- $^h$ From 241 to 245 d

$P_{\text{rot}}$: Rotational period; $T_{\text{eff}}$: Effective temperature; $E_{\text{ej}}$: Energy of the ejection; $A_{\text{ej}}$: Area of the ejection.
| CoRoT ID   | Type  | $P_{rot}$ (days) | $T_{\text{eff}}$ (1000 K) | $E_{\text{int}}$ (erg) | $A_{\text{int}}$ (cm$^2$) |
|-----------|-------|-----------------|--------------------------|------------------------|--------------------------|
| 223968260 | K0V   | 1.645 ± 0.001   | 5.26 ± 0.70              | 5.6 ± 0.70             | 7.138 ± 10.52            |
| 110660270 | K0V   | 1.969 ± 0.001   | 5.77 ± 0.74              | 5.4 ± 0.74             | 10.52 ± 10.52            |
| 110757572 | K0V   | 6.676 ± 0.002   | 4.60 ± 0.51              | 4.7 ± 0.51             | 10.52 ± 10.52            |
| 211607099 | K0V   | 0.974 ± 0.001   | 10.3 ± 2.3               | 10.3 ± 2.3             | 10.3 ± 2.3               |
| 101282630 | K1III | 13.866 ± 0.004  | 4.15 ± 0.48              | 4.15 ± 0.48            | 4.15 ± 0.48              |
| 104939145 | K1III | 26 ± 6          | 5.96 ± 0.77              | 5.96 ± 0.77            | 5.96 ± 0.77              |
| 10046118   | K1III | 4.024 ± 0.002   | 5.02 ± 0.50              | 5.02 ± 0.50            | 5.02 ± 0.50              |
| 223988965  | K1III | 3.4 ± 0.5      | 5.18 ± 0.73              | 5.18 ± 0.73            | 5.18 ± 0.73              |
| 101309841  | K2III | 8.587 ± 0.007   | 4.42 ± 0.62              | 4.42 ± 0.62            | 4.42 ± 0.62              |
| 105271299  | K2III | 10.48 ± 0.03    | 3.93 ± 0.52              | 3.93 ± 0.52            | 3.93 ± 0.52              |
| 110669882  | K2III | 8.052 ± 0.003   | 4.58 ± 0.66              | 4.58 ± 0.66            | 4.58 ± 0.66              |
| 500007248  | K3I   | 3.78 ± 0.02     | 5.57 ± 0.85              | 5.57 ± 0.85            | 5.57 ± 0.85              |
| 102646977  | K3II  | 20.8 ± 0.3      | 9.5 ± 2.1                | 9.5 ± 2.1              | 9.5 ± 2.1                |
| 500007323  | K3II  | 6 ± 1           | 7.2 ± 1.4                | 7.2 ± 1.4              | 7.2 ± 1.4                |
| 102379742  | K3III | 0.4231 ± 0.0008 | 3.90 ± 0.51             | 3.90 ± 0.51            | 3.90 ± 0.51              |

Table 2
(Continued)
...will be present. In this case, the period is defined as the gradient of a straight-line fit to the ACF peak positions as a function of peak number, to obtain a more robust determination of the period and its uncertainty (see McQuillan et al. 2014, for details). In some cases, the estimated errors are very small and were arbitrarily made equal to 32 s. We visually inspected the light curves and their periodograms to check the estimated period. One of the advantages of the ACF method is its potential to give the correct rotation period even when there are two diametrically opposite active regions or, in the case of a close contact binary, when the two minima have similar depths. This is the case for CoRoT 102854684, CoRoT 102718810, and CoRoT 223993277, where the first two are probably eclipsing binary systems. Klagyivik et al. (2017) obtained orbital periods for them that agree with ours within 2σ, by removing the signature of an eclipsing binary from the light curve to look for transit-like features.

Two of the analyzed stars (CoRoT 102615551 and CoRoT 223983509) are in the eclipsing binary catalog of the CoRoT/Exoplanet program (Deleuil et al. 2018). The two aforementioned likely binaries reported by Klagyivik et al. (2017) are not among them. As CoRoT 102615551 has very deep and narrow eclipses (Carone et al. 2012), we report in Table 2 the value given by Deleuil et al. (2018). The other object, CoRoT 223983509, identified as a contact binary by Deleuil et al. (2018), has an orbital period that agrees with ours within 1σ, and it has also been identified as a T Tauri star (Venuti et al. 2015). Ten of our stars are members of the star-forming region NGC 2264 (~3 Myr) and were classified as weak-lined T Tauri stars (Venuti et al. 2015). In young stellar objects and binary stars, flare events can originate from magnetic reconnection in the field that connects the star to the accretion disk or to the other star, as the case may be. There is only one case (CoRoT 110741064) in which no periodic variation was detected.

![Figure 9](image-url)

*Figure 9. Flare temperature $T_{\text{flare}}$ (k) (as in the top panel of Figure 6) vs. stellar rotation period. The horizontal error bars correspond to the uncertainty in the estimated rotation period, which is very small in most cases. Two flares with temperatures larger than 30,000 K have uncertainties around 10,000 K, and their error bars are not shown for a better visualization. Stars identified as T Tauri are shown in red, and eclipsing binaries in blue, and their flare temperatures are connected by a dotted line of the same color. CoRoT 223983509 is shown in green, as it has been classified as T Tauri and eclipsing binary. In the case of binaries, the period shown is their orbital period.*

**Table 2**

(Continued)

| CoRoT ID   | Type | $P_{\text{rot}}$ (days) | $T_{\text{flare}}$ (1000 K) | $E_{\text{flare}}$ (erg) | $A_{\text{flare}}$ (cm$^2$) |
|------------|------|-------------------------|-----------------------------|--------------------------|-----------------------------|
| 102602133  | K5III| 21.3 ± 0.1              | 4.75 ± 0.85                 | (42.0 ± 3.2) × 10$^{35}$ | (36.9 ± 1.9) × 10$^{35}$    |
| 102602133  | K5III| 6.5 ± 1.4               | 4.84 ± 0.87                 | (37.4 ± 1.3) × 10$^{35}$ | (151.2 ± 5.6) × 10$^{35}$   |
| 102602133  | K5III| 3.70 ± 0.62             | 5.6 ± 1.1                   | (54.5 ± 4.9) × 10$^{35}$ | (21.1 ± 1.1) × 10$^{20}$    |
| 106048015  | K5III| 15.430 ± 0.009          | 6.5 ± 1.7                   | (36.0 ± 5.2) × 10$^{34}$ | (55.7 ± 6.5) × 10$^{24}$    |

Note. Their spectral type is given by the ExoDat Database. Flares observed at different epochs (taken ~4 yr apart) are marked with a star next to their temperature. A small letter after the rotation period indicates an eclipsing binary identified by Deleuil et al. (2018), by Klagyivik et al. (2017), and a T Tauri analyzed by Venuti et al. (2015). The value in the $P_{\text{rot}}$ column for eclipsing binaries is actually their orbital period. In the case of the eclipsing binary CoRoT 102615551, the value obtained by Deleuil et al. (2018)—marked with the * symbol—is given. Due to the large uncertainties, there are flares with the same temperature and uncertainty for some stars. (This table is available in machine-readable form.)

6. Calibration

The accuracy of Gaia photometry is better than any other major catalog currently available, even more so with the improvements from Gaia Early Data Release 3 (Gaia...
EDR3 Gaia observations that are more than 1° away from the CoRoT target are marked with a $d$, and the two that are fainter than expected are indicated by an $F$.

(This table is available in machine-readable form.)

EDR3 Gaia observation corresponding to CoRoT 102379742 does not have an estimated parallax and has been replaced by Gaia DR2 (labeled “$R^2$”). The three EDR3 Gaia observations that are more than 1° away from the CoRoT target are marked with a $d$, and the two that are fainter than expected are indicated by an $F$.

The $G$ band is very similar to the CoRoT White channel (see, e.g., Figure 1 in Nèmec et al. 2020) to calibrate the analyzed flare magnitude.

First, we searched the Gaia EDR3 for stars at the same coordinates ($\alpha$, $\delta$) as ours. We compared their coordinates differences and iteratively removed outliers. We ended up with a standard deviation of 0.15 in $\alpha$ and $\delta$. We selected only stars of Gaia that differ by less than 0.6 ($4\sigma$) in $\alpha$ and $\delta$ and whose angular distance is less than 0.02° from the CoRoT coordinates; we found 66 out of 69 stars. The stars observed by Gaia that are closer to the three missing ones (CoRoT 102948867, CoRoT 110685010, and CoRoT 221647275) are 1°, 2°, and 2° away, respectively. Table 3 shows the corresponding Gaia ID EDR3.

In Figure 10, we plotted GAIA $G$-band mean apparent magnitude (phot $g$ _mean_mag), which is computed from the $G$-band mean flux applying the magnitude zero-point in the Vega scale, in the VEGAMAG photometric system (Equation (1) in Andrae et al. 2018) versus the CoRoT magnitude in the White channel given by $-2.5 \log_{10} F_{\text{white}}$. The CoRoT flux is in electrons per 32 s (Chaintreuil et al. 2016). After fitting a straight line to 66 stars and removing outliers from the residuals larger than 4$\sigma$ (open blue circles), we fitted again a straight line through the selected filled circles (corresponding to 64 stars) and obtained

$$G = c_0 + c_1 \cdot m_{\text{CoRoT}},$$

where $c_0 = 27.6 \pm 0.3$ mag and $c_1 = 1.05 \pm 0.02$. The two discarded outliers, CoRoT 500007248 and CoRoT 500007323, are fainter than expected in the White channel, which may be due to an observational artifact or misidentification due to field contamination. Each of these stars contributes with only one flare in our analysis. There are eight stars in our set that have been observed twice (in 2008 and 2012). Their two CoRoT magnitudes are connected with a red horizontal line in Figure 10. The flare peak flux, $a_0$, observed in the White channel (Equation (1)), can be converted to GAIA $G$-band magnitude using Equation (10):

$$G_p = c_0 - 2.5c_1 \log_{10}(a_0).$$

The uncertainty in estimating the $G$-band flare peak was obtained using standard error propagation. There is no perceptible dependence of the $G$-band flare peak, $G_p$, on the stellar magnitude, $G$. 

Note: The EDR3 Gaia observation corresponding to CoRoT 102379742 does not have an estimated parallax and has been replaced by Gaia DR2 (labeled “$R^2$”).
Using Equation (10), the average apparent stellar magnitude of our 69 stars and its standard deviation are equal to $G = 13.6 \pm 0.8$ mag. However, their distances, $d$, range from 37 pc to 6.2 kpc. These stars are all in the galactic disk, as the CoRoT observations were in an area toward the Galactic center and another at the Galactic anticenter. We calculated the absolute stellar magnitude $M_G = G - 5 \log_10 d + 5$ and similarly the absolute magnitude of the flare peak, $M_{G,P}$, without taking the extinction into account. The flare peak amplitudes are in the range of 4 mag < $M_{G,P}$ < 14 mag. There is a good correlation between them (Figure 11). Fitting a straight line, we obtained

$$M_{G,P} = (4.12 \pm 0.09) + (0.98 \pm 0.01)M_G. \quad (12)$$

For a linear coefficient equal to 1, we have that the peak flare flux is $\sim 2.5\%$ of the stellar flux in the Gaia $G$ band.

The Gaia flare energy, $E_{G,f}$, was calculated by multiplying the flare ED (Equation (2)) observed in the White channel, measured in units of time, by the stellar luminosity in the Gaia bandpass filter:

$$E_{G,f} = E_{D, \text{White}} \cdot L_G. \quad (13)$$

As the flare ED varies with the observed bandpass filter by two or more orders of magnitude (Hawley et al. 2014), we did not attempt to estimate the bolometric energy. To calculate the stellar luminosity in Gaia’s $G$ band, $L_G$, we first converted mean flux $f_G$ (phot.g_mean_flux [e$^-$ s$^{-1}$]) into mean energy (W m$^{-2}$ nm$^{-1}$) by multiplying it by $c_\lambda = 1.346109 \times 10^{-21}$ as described in the Gaia photometric calibration (Montegriffo 2021). Then, we multiplied the stellar energy by $4\pi d^2$ and by Gaia filter FWHM, $\Gamma_G$, to obtain $L_G$ (as in Hawley et al. 2014):

$$L_G = f_G \cdot c_\lambda \cdot 4\pi d^2 \cdot \Gamma_G, \quad (14)$$

where $\Gamma_G = 454.82$ nm (Table 3 in Riello et al. 2021). The observed flare energies are in the range $10^{32}$ erg $< E_{G,f} < 10^{37}$ erg and are given in Table 2. The energy of 16 flares observed at five stars, for which we did not find a good match with Gaia observations (labeled in Table 3), was not used in our analysis, and their values in the table should be used with caution. Fitting a straight line to the logarithm of the flare energy as a function of the logarithm of the stellar luminosity, we get

$$E_{G,f} = (4 \pm 1) \times 10^{-6} L_G^{1.218 \pm 0.005}, \quad (15)$$

where $E_{G,f}$ and $L_G$ are in erg and erg s$^{-1}$, respectively. Flare energy exponentially increases with stellar luminosity. As in Figure 6 (second row), the top panel in Figure 12 shows the flare energy in intervals of half-spectral type of its star, where the energies are in ascending order inside each range. The weighted average of the flare energy over each interval is in the bottom panel. The dashed (dotted) line indicates the weighted (unweighted) average of the mean energy including all stellar luminosity classes (black circles). There is some weak indication of a possible increase of flare energy for late-type stars.

Howard et al. (2020) reported a weak correlation between the flare temperature, integrated over the entire flare, and flare energy in the $g^\prime$ band. We do not see any indication of a dependence between our estimation of flare energy in the Gaia $G$ band and flare temperature. Furthermore, we do not see a variation of the flare energy with the stellar rotation (Figure 9). We looked for a complex dependence using the theoretical estimate by Namekata et al. (2017) of the bolometric flare energy:

$$E_{\text{bol}} = c d^3 B^4, \quad (16)$$

where $c = 5.8 \times 10^{19}$ erg minute$^{-3}$ G$^{-5}$. In addition to the implication that a flare with a longer duration ($d$) will have higher energy, they also deduced, considering the dependence of the Alfvén velocity on the magnetic field, that a stronger local magnetic field $B$ will imply a flare with larger energy. It is expected that greater amounts of magnetic energy stored, for example, at large spots lead to more energetic flares (e.g., Candelaresi et al. 2014). The coefficient $c$ was estimated from the average values of their solar flare observations, which are $d = 3.5$ minutes, $E_{\text{bol}} = 1.5 \times 10^{30}$ erg, and $B = 57$ G.

Figure 13 shows the flare energy in the Gaia band versus the flare duration given by the $e$-folding rise time plus the $e$-folding decay time observed by CoRoT. In the top panel, the different colors correspond to four different stellar rotation ranges, and in the bottom panel, they correspond to three different flare temperature intervals. Similarly to the relation given by Equation (16), the panels show, for various values of $B$, the following relationship: $E_{G,f} = c'd^3 d_B^4 B^4$, where $c' = 3.7 \times 10^{18}$ erg minute$^{-3}$ G$^{-5}$. To obtain $c'$, we arbitrarily increased the flare duration value by 25% to account for the flare rising phase (not included before) and divided their bolometric energy estimate by 8 to adjust for the flare energy in the Gaia $G$ band. This factor was roughly estimated using the relation in Equation (13), where we assumed that the flare duration in the Gaia passband is the same as that at all wavelengths, we used the GAIA DR2 estimate of stellar luminosity (“lum_val”), and we extrapolated to the low value of the average solar flare energy. Namekata et al. (2017) also used the duration of the flare observed in visible light (more specifically, in the SDO/HMI’s narrow passband around the FeI λ6173.3 line) to estimate the flare bolometric energy. Since the $c'$ coefficient was not precisely determined, all straight lines in Figure 13 might be horizontally displaced by a small amount. We can see...
in the top panel that the areas observed in fast rotators, $P_{\text{rot}} < 1$ day (blue circles), are associated with magnetic fields slightly larger than $\sim 200$ G, while slower rotators, 7 days $\leq P_{\text{rot}} < 20$ days (red circles), are mostly associated with $B$ slightly smaller than $\sim 200$ G. Interestingly, flares in stars with longer rotation periods, $P_{\text{rot}} > 20$ days (black circles), unexpectedly correspond to large magnetic fields ($B \gtrsim 800$ G). These nine flares were observed on four stars (CoRoT 102602133, CoRoT 102631863, CoRoT 104939145, and CoRoT 102646977), none of which were identified as an eclipsing binary star or a T Tauri star. Four of these flares were observed on CoRoT 102602133, but only one corresponds to a lower magnetic field as expected ($B \lesssim 200$ G). This flare also differs from the others for having a much longer duration and a lower temperature: $T_{\text{flare}} \approx 3700 \pm 600$ K. One of the flares on a star with $P_{\text{rot}} > 20$ days (black circles) has a very high temperature: $T_{\text{flare}} = 21,100 \pm 6800$ K (the one with $E_{GJf} = 1.8 \times 10^{36}$ erg in the figure) in contrast to the low temperature just mentioned. The bottom panel shows the variation with the flare temperature, where we see no clear interrelationship. We note, however, that flares with $T_{\text{flare}} < 5000$ K (black symbols) correspond to $B \lesssim 400$ G. In addition, most high-temperature flares ($\gtrsim 14,000$ K) are short-lived (less than 10 minutes). For 40% of flares that last less than 10 minutes, the ascending phase is longer than the descending phase (i.e., $\alpha_2 < \alpha_3$ in Equation (1)). These flares correspond to 12% of the analyzed flares, and all but two have a duration smaller than 10 minutes.

We estimated the area of the flares, $A_{\text{flare}}$, observed by the CoRoT White channel using Equation (6) in units of energy, where the stellar luminosity, $L_G$, is given by Equation (14). The flare area varies by 5 orders of magnitude, from $10^{18}$ to $10^{23}$ cm$^2$, i.e., 30 $\mu$s to 3 $s$ (solar hemisphere), and is displayed in Table 2. The area uncertainty was estimated by propagating the errors of $E_D$, duration, $L_G$, and flare surface brightness. Figure 14 (top panel) shows the variation of flare area with flare energy. The flare area increases (almost linearly) with flare energy: $\log_{10} A_{\text{flare}} = - (7.87 \pm 0.09) + (0.830 \pm 0.002) \log_{10} E_{GJf}$, in cgs units (shown as a red line in the top panel), This is expected (Equations (6) and (13)), as well as that the flare area is proportional to $L_G^{1.144 \pm 0.003}$. The stellar luminosity is proportional to its surface area, for a given effective temperature; therefore, in principle, the area of the flare is increasing with the area of the star. However, we do not observe any clear dependence of flare area on spectral type or luminosity class in our data. Figure 14 (middle panel) shows the variation of flare area with flare temperature. For $T_{\text{flare}} \lesssim 7500$ K, the flare area decreases, in most cases, as temperature increases. Analyzing the flare energy-to-area ratio versus temperature (Figure 14, bottom panel), we did a log–log fit and obtained that the ratio, in cgs units, is proportional to $T_{\text{flare}}^{-2.35 \pm 0.03}$ (red dashed line). It seems that there is a change in behavior where, for flares with $T_{\text{flare}} > 10,000$ K, the ratio seems to be constant, and its weighted average is equal to $E_{GJf}/A_{\text{flare}} = 1.7 \times 10^{14}$ erg cm$^{-2}$ (horizontal dotted blue line). Fitting again now only for $T_{\text{flare}} < 10,000$, we obtain $E_{GJf}/A_{\text{flare}} \propto T_{\text{flare}}^{2.60 \pm 0.04}$ (red solid line). As the temperature percentage uncertainties increase with temperature and the number of flares decreases, this possible saturation at $T_{\text{flare}} \gtrsim 10,000$ K should be regarded with caution.

Figure 12. Top: Gaia flare energy as a function of spectral type, going from late- to early-type stars, in intervals of half a spectral class. The spectral type at the center of each interval is indicated at the bottom of the plot. The flare energies are in ascending order inside each interval. The different colors represent the different luminosity classes, as in Figure 6, where classes I to V are in red, orange, blue, cyan, and, green respectively. Bottom: weighted average of the flare energy as a function of the average spectral subclass corresponding to the flares within each interval of half a spectral class shown in the top panel. The averages for a given luminosity class, when there are four or more flares, are shown in different colors (as in the top panel). The averages including all luminosity classes are shown in black. The vertical error bars correspond to the standard deviation of the flare energy weighted average, and the horizontal error bars correspond to the standard deviation of the average of the spectral subclass. The absence of a horizontal bar means that only one spectral type was used in the energy averaged.
7. Conclusions

Assuming that the spectrum of WLFs can be described by blackbody radiation, we determined the effective temperature for more than 200 flares observed by CoRoT in 69 F-, G-, and K-type stars. The temperatures were obtained using the flare ED and stellar flux observed in the Blue and Red channels. The wavelength limits for the color channels were estimated using stellar spectra from the Pickles library for the spectral type and luminosity class of the star given by the Exodat Database. We took the uncertainties in the stellar classification into account and carefully propagated them in our estimate of the flare temperature.

The estimated flare temperatures vary from 3000 to 30,000 K. Its uncertainties steadily increase from 10% at 3000 K to about 40% at 25,000 K, as the blackbody radiation maximum moves toward UV wavelengths and out of the CoRoT Response Function. The expected value of the temperature distribution of the 209 analyzed flares is equal to 6400 K with a standard deviation of 2800 K. These flares have been observed in A5–K5 stars. The mean spectral type, weighted by the number of flares in each spectral subclass, is equal to G6. The narrowest range that includes 75% of the temperature distribution occurs between 3400 and 8100 K. Only 24 stars (35%) of the analyzed stars have three or more flares with an estimated flare temperature. In most of them, the temperature variation of the flares observed on the same star is within the individual uncertainties, except for 10 stars. The largest variation is for CoRoT 223993277 (shown in Figure 7), which has a standard deviation equal to 70% of its mean temperature.

It is often assumed that a stellar flare is radiated by a blackbody with a temperature of 9000 K or 10,000 K (see...
The estimated temperature pdf (shown as a blue line in Figure 8) gives a 6% probability that the temperature is within 9000 ± 500 K and even lower around 10,000 K. The probability increases to 21% at 5300 ± 500 K (i.e., at the mode). If we disregard the temperature uncertainties that give less weight to high temperatures, the pdf (shown as a red solid line in Figure 8) is more spread and the probability increases to 8% at 9000 ± 500 K, while it decreases to 15% at its mode (5800 ± 500 K). In conclusion, our results do not favor 9000 K or higher as a representative value for the flare temperature. However, they agree with estimates of solar WLFs, around 6000 K.

M-type stars are known to have many energetic flares (e.g., Maehara et al. 2021). Nonetheless, our analysis suggests that the mean flare temperature decreases in stars from early to late type by 1800 ± 1400 K per spectral type. The average temperature seems to decrease from ~6000 K for flares in G6-type stars, the average spectral type of the analyzed stars, to less than 4000 K in M stars. Furthermore, we found no indication that an energetic flare (observed by the CoRoT White channel) has a high temperature. The extrapolated low-temperature value for M stars does not agree with other estimations using observations in the visible. Flares on the M-dwarf AD Leo were estimated to have a blackbody temperature of ~9000 K by Hawley et al. (2003) and 14000 ± 8000 K by Namekata et al. (2020), while the values obtained by Howard et al. (2020) for 40+ flares observed on K5–M5 dwarfs have a median of 7500 K and a large standard deviation, equal to 6600 K, with values ranging from 4400 to 50000 K (given by “Total $T_{\text{eff}}$” in their Table 1).

We calibrated the amplitude and energy of the analyzed flares observed in the White CoRoT channel to the Gaia photometric system. The absolute magnitude in the Gaia G band of the analyzed stars varies from 0 to 10 mag, while the flare peaks vary from 4 to 14 mag. The flare luminosity during its maximum is, on average, ~2.5% of the stellar luminosity in the G band ($L_{\text{G}}$). The $G$-band flare energy was calculated by multiplying $L_{\text{G}}$ by the ED of the flare observed in the CoRoT White channel. The Gaia flare energy varies between $10^{32}$ and $10^{37}$ erg and is roughly proportional to $L_{\text{G}}^{1.22}$.

There is no simple or clear dependence between flare temperature, duration, energy, stellar rotation period, and local magnetic field. The latter was included in our comparison using the relation given by Namekata et al. (2017), where the flare energy is proportional to the cube of its duration and the fifth power of the local magnetic field. We arbitrarily divided the stars into four rotation period intervals. For our flare sample, we observed that flares in stars with $P_{\text{rot}} < 1$ day appear to have short duration ($<20$) and low energy ($<10^{36}$ erg) with $B = 200 - 400$ G, while flares in stars with $P_{\text{rot}} = 7 - 20$ days have the opposite behavior, that is, long duration ($>20$) and high energy ($>10^{34}$ erg) with $B < 200$ G. Flares in stars with intermediate rotation period, $P_{\text{rot}} = 1 - 7$ days, have a wide range of duration, energy, and magnetic field. Unexpectedly, stars with a long rotation period, $P_{\text{rot}} > 20$ days, are associated with larger magnetic fields ($B > 800$ G), with shorter duration ($<10^3$) and higher energies ($>10^{35}$ erg). We do not notice any correlation with flare temperature, except for some evidence that low-temperature flares ($T_{\text{flare}} < 5000$ K) do not have strong magnetic fields ($B > 400$ G).

We estimated the flare area based on our flare temperature estimate and by calibrating the CoRoT observations to the Gaia photometric system. Observed in the Gaia G band, the flare area increases with flare energy as $E_{\text{flare}}^{0.83}$ in cgs units, varying from $3 \times 10^{-5}$ sh to 3 sh (solar hemisphere). Assuming that the flare ribbon area is similar to the spot area (e.g., Toriumi et al. 2017), these values range from 2 orders of magnitude smaller to 3 times larger than spot areas reported by others. Okamoto et al. (2021) estimated spot areas between $1.6 \times 10^{-3}$ sh and $13 \times 10^{-3}$ sh for Sun-like stars, while Herbst et al. (2021) found, for K–M stars, spot areas ranging from $5 \times 10^{-3}$ sh to 1 sh. Although it increases almost linearly with Gaia stellar luminosity, we did not find a variation with spectral type or luminosity class. A careful stellar classification using spectroscopic observations would help clarify this.

The lack of high-cadence, long-duration observations of stellar spectra or high-precision photometry in multiple (more than one) passband filters obtained simultaneously has hampered the determination of the temperature of the flares. Hence, their quantity is small. This work significantly increases the number of temperature determinations. Furthermore, it shows the importance of multifilter space missions like Plato (Rauer et al. 2014, 2016). To the best of our knowledge, this is the first estimation of WLF temperature for G dwarfs other than the Sun using multicolor photometry. While there is still some doubt that the observed flaring G dwarfs are indeed Sun-like stars (Cliver et al. 2022), the possibility remains that the Sun is capable of producing flares as energetic as those observed in other stars, dubbed superflares. Furthermore, the study of superflares in stars of the same spectral class as our Sun is relevant not only for the possibility that this happens on our Sun but also in the search for life on exoplanets (Maehara et al. 2012; Namekata et al. 2021). Superflares may produce coronal mass ejections much larger than the largest observed on the Sun and affect the environment, habitability, and development of life on nearby exoplanets (Airapetian et al. 2020).

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**Facilities:** CoRoT, Gaia.

**Software:** IDL, matplotlib (Hunter 2007), astroPy (Astropy Collaboration et al. 2013, 2018), LMFIT (Newville et al. 2021), scipy (Virtanen et al. 2020).

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