

Flares in Open Clusters with K2.

II. Pleiades, Hyades, Praesepe, Ruprecht 147, and M67

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ABSTRACT

Context. Flares are energetic magnetic eruptions on the surfaces of stars, and thereby unmistakeable manifestations of stellar activity. Stellar evolution on the main sequence is intimately tied to stellar activity in general, and flaring activity in particular.

Aims. This work set out to quantify flaring activity of independently age-dated main sequence stars for a broad range of spectral types using optical light curves obtained by the Kepler satellite.

Methods. Drawing from the complete K2 archive we searched 3435 light curves of open cluster members for flares using the open-source software packages K2SC and AltaiPony. K2SC was used to remove instrumental and astrophysical variability from K2 light curves, and AltaiPony to search and characterize the flare candidates.

Results. We confirmed a total of 3844 flares on high probability open cluster members with ages from Pleiades (ZAMS) to M67 (3.6 Gyr). We extended the mass range probed by Ilin et al. (2019) to span Sun-like stars to mid M dwarfs. We supplemented the Hyades (690 Myr) as a comparison cluster to Praesepe (750 Myr), the 2.6 Gyr old Ruprecht 147, and several hundred additional light curves in the remaining clusters. We found that the flare production mechanism was similar in the entire parameter space, following a power law relation with exponent $\alpha \approx 2.0 - 2.1$. We confirmed that flaring activity declined with age, and declined faster for higher mass stars. We noticed good agreement with most of the more recent statistical flare studies. We concluded that discrepancies between our results and flare studies that used rotation periods for their age estimates could be explained by sample selection bias but may also hint at limitations to rotation as an age indicator.

Key words. Methods: data analysis, Stars: activity, Stars: flare, Stars: low-mass

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1. Introduction

Flares are explosions on stellar surfaces with a complex spatio-temporal and energetic phenomenology. We know that flares are magnetic re-connection events that lead to a change in field line topology and subsequent energy release (Priest & Forbes 2002). We can observe flares in nearly all electromagnetic bands, from radio to X-ray, and on all stars that possess a convection zone, from late F type stars to ultracool dwarfs (Schaefer et al. 2000; Benz & Güdel 2010; Gizis 2013).

Stellar flares on cool stars can enhance the optical flux by up to several orders of magnitude within minutes or seconds (Haisch et al. 1991). They typically exhibit blackbody emission at temperatures significantly higher than these stars' photospheres (Hawley & Fisher 1992a). The high intensity and contrast allow us to measure magnetic activity as traced by flares for a broad range of stars.

Statistical flare studies have been pioneered from the ground (Lacy et al. 1976). But it was not until space missions like Kepler (Koch et al. 2010) and the Transiting Exoplanet

Survey Satellite (Ricker et al. 2014) enabled the investigation of stellar ensembles that were not pre-selected for their activity (Walkowicz et al. 2011). Statistical studies of stellar flaring activity can help us understand the underlying physical processes of flares (Benz & Güdel 2010), the nature of stellar surface magnetic fields, starspots (Davenport 2015; Howard et al. 2020), how flares relate to stellar angular momentum evolution (Mondrik et al. 2019; Howard et al. 2020), and how they affect the atmospheres of exoplanets (Lecavelier des Etangs et al. 2012; Loyd et al. 2018; Tilley et al. 2019; Howard et al. 2019).

The present study has a focus on the relation between flares and stellar evolution of low-mass stars on the main sequence. To this end, we set out to quantify how flaring activity changes as a function stellar mass and age.

In main sequence stars, flaring activity is known to increase in intensity down to spectral type M5 (Chang et al. 2020), and continue into the ultracool dwarf regime (Schmidt et al. 2015; Schmidt et al. 2016; Paudel et al. 2018). In fact, the prototype flare star, UV Ceti, is an M6 dwarf (Kirkpatrick et al. 1991).

Flaring activity decays with age. However, stellar ages can only be determined indirectly. Using galactic latitude as a proxy for age, flaring activity appeared to decline with higher galactic latitude, that is, older age, for M dwarfs (Hilton et al. 2010; Walkowicz et al. 2011; Howard et al. 2019). In gyrochronology, fast rotation indicates young age (Barnes 2003), and slows down as the star ages. So the relation between rotation and flaring can be used to calibrate a flaring-age relation (Davenport et al. 2019). Chromospheric activity was also explored as an age tracer in the past (Soderblom et al. 1991; Pace 2013; Lorenzo-Oliveira et al. 2016). **This also suggests that an age calibration of flaring activity is possible because a significant portion of flaring energy is emitted in $H\alpha$** (Kowalski et al. 2013).

While absolute stellar ages are difficult to assess, they can at least be differentially controlled for in coeval groups of stars. Flaring-age studies in binaries showed consistent activity for both components in the majority of targets (Lurie et al. 2015; Clarke et al. 2018). Open clusters (OC) are also coeval groups of stars with well-determined ages from isochrones that have been used as a laboratory for flare studies on stars with a fixed age (Mirzoyan 1993; Chang et al. 2015). Ilin et al. (2019) (hereafter PaperI) investigated the flaring activity of late-K to mid-M dwarfs in three OCs, the Pleiades, Praesepe, and M67, using K2 time domain photometry. They analyzed flare frequency distributions (FFDs) broken down by the stars' effective temperatures T_{eff} and ages. They found that flaring activity declined both with increasing mass and age, and that the trend was more pronounced for higher mass stars.

This study aimed to extend the results in PaperI to the age of Ruprecht 147 (Rup 147, 2.5 Gyr), and both higher and lower masses than in the previous study. We used the now complete K2 data set, supplemented all three OCs in PaperI with improved versions of already treated light curves in Campaigns 4 and 5, and added light curves from later Campaigns. The light curve catalog, and the determination of cluster membership and effective temperature for the investigated stars are detailed in Section 2. We used a semi-automated flare finding procedure, described how we estimated flare energies, and how we parametrized the statistical properties of flares in Section 3. We present our findings in Section 4. We placed our results in the context of recent flare studies, and reflected on the power law nature of FFDs in Section 5. Recently, Davenport et al. (2019) proposed an empirical parametrization of the flaring-mass-age relation based on FFDs of stars with gyrochronologically determined ages, which we also put to test in the discussion. The summary and conclusions can be found in Section 6.

2. Data

This work is based on K2 30-minute cadence light curves that were provided by the Kepler archives hosted at the Barbara A. Mikulski Archive for Space Telescopes (MAST). We used multiband photometry from several all-sky surveys to assign T_{eff} , and gathered OC membership information from the literature to estimate the ages. An overview over the cluster sample is presented in Table 1 and illustrated in Figure 1.

2.1. K2 light curves

The Kepler (Koch et al. 2010) spacecraft finished its follow-up mission K2 (Howell et al. 2014) in September 2018, after having completed nearly 20 80-day observing campaigns. Although Kepler and K2 data were already used in more than 2400 publications in 2018, the public archive was still considered

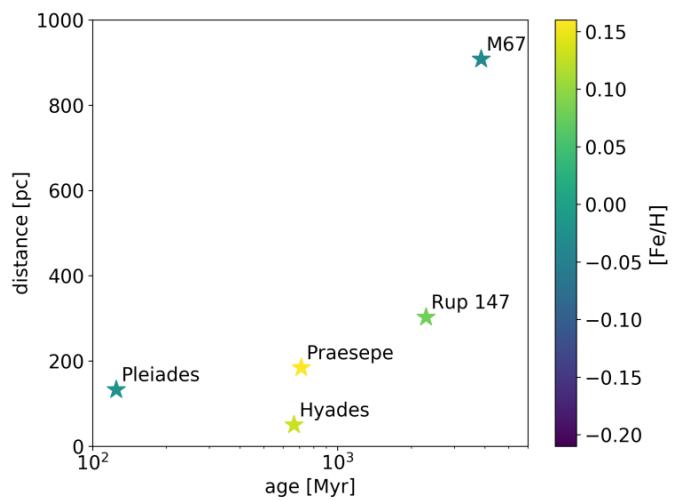


Fig. 1. Age plotted against distance of open clusters (star symbols) that we searched for flares, colored by [Fe/H]. Age, distance, and [Fe/H] are approximate values from a compilation of existing literature, see Appendix B.

understudied (Barentsen et al. 2018). In this spirit we took up the analysis of a total of 3435 light curves where each light curve contained up to 80 uninterrupted days of 30 min cadence observations in white light ($4,200 - 9,000 \text{ \AA}$).

As K2 was conducted on the two-wheeled Kepler satellite, it was subjected to substantial drift motion (spacecraft roll, Van Cleve et al. 2016) and had an overall reduced pointing accuracy. To mitigate these effects, various solutions were developed (Vanderburg & Johnson 2014; Aigrain et al. 2016; Luger et al. 2016; Luger et al. 2018). We used the K2 Systematics Correction (K2SC) pipeline (Aigrain et al. 2016) with minor modifications to de-trend the 36th data release of the K2 data products. This data release was final, and included a uniform, global reprocessing of most K2 campaigns using an improved data reduction pipeline¹.

2.2. Open Clusters

We obtained membership information from multiple catalogs for each OC. We cross-matched these catalogs on RA and declination within 3 arcsec. The resulting target lists were used to search the K2 archive. One part of the membership catalogs provided membership probabilities (Douglas et al. 2014; Cantat-Gaudin et al. 2018; Olivares et al. 2018; Reino et al. 2018; Gao 2018; Olivares et al. 2019). For the other part no probability was quoted (Rebull et al. 2016; Douglas et al. 2017; Gaia Collaboration et al. 2018a), or qualitative classifiers were given (Curtis et al. 2013; Gonzalez 2016; Rebull et al. 2017). In the latter cases we assigned approximate probabilities anchored to the set threshold for inclusion into our final sample (Appendix A). Absence in a catalog did not decrease the likelihood of membership, as each catalog had different selection biases which we did not address in this study. We set the threshold mean membership probability p for a target in our sample to 0.8.

We studied flaring activity in the low mass stars in five OCs spanning ages from ZAMS to roughly solar. Table 1 provides an overview over the final sample of stars and flares. Membership probability histograms of the final sample are displayed in Figure

¹ <https://keplerscience.arc.nasa.gov/k2-uniform-global-reprocessing-underway.html>

A.1 in Appendix A. A literature overview of age, distance, and metallicity determinations is given in Table B.1 in Appendix B.

2.2.1. Pleiades

The Pleiades, a nearby ZAMS cluster, was observed in Campaign 4, and treated in PaperI. Here, we used 741 reprocessed K2 light curves from this OC, and our methodological improvements to PaperI to repeat the analysis. We revisited the members from Rebull et al. (2016), which were used in PaperI, and merged the catalog with lists of members determined by Olivares et al. (2018); Gaia Collaboration et al. (2018a); and Cantat-Gaudin et al. (2018).

2.2.2. Hyades

The Hyades are a 690 Myr old OC that was observed during Campaigns 4 and 13 with K2. We merged membership tables obtained from Douglas et al. (2014); Reino et al. (2018); and Gaia Collaboration et al. (2018a) to select 170 high confidence members, of which 9 were observed in both K2 campaigns.

2.2.3. Praesepe

Praesepe (750 Myr) is only a little older than the Hyades. The OC was observed during Campaign 5, and was also treated in PaperI. It was observed again during campaigns 16 and 18. We revisited the membership catalog from Douglas et al. (2014), and matched it to the members identified in Douglas et al. (2017); Rebull et al. (2017); Cantat-Gaudin et al. (2018); and Gaia Collaboration et al. (2018a). This was the richest sample with over 900 stars and nearly 2000 light curves.

2.2.4. Ruprecht 147

Rup 147 is a 2.5 Gyr old OC observed during Campaign 7 with K2. We used the mean membership probabilities obtained from Curtis et al. (2013); Cantat-Gaudin et al. (2018); Olivares et al. (2019), and Gaia Collaboration et al. (2018a) to identify the 53 most likely members.

2.2.5. M67

M67 is a 3.6 Gyr old OC about 900 pc away. 234 members were observed during campaign 5, 16 and 18. We did not find any flares in M67 in Campaign 5 (PaperI) light curves of members identified by Gonzalez (2016). Campaigns 16 and 18 delivered both additional observations, and new targets to the sample in (PaperI), yielding almost 500 light curves for this OC. We merged the members from Gonzalez (2016) with a recent study based of Gaia DR2 data (Gao 2018).

2.3. Effective temperatures, stellar radii, and luminosities

We determined effective temperatures T_{eff} using broadband photometry from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) Data Release 1 (Pan-STARRS DR1; Chambers et al. 2016), and Gaia Data Release 2 (Gaia DR2; Gaia Collaboration et al. 2016b, 2018b). We applied quality cuts to 2MASS, Pan-STARRS DR1, and Gaia DR2 data, as described in Appendix C, and removed foreground stars using Gaia DR2 parallaxes. We corrected the

2MASS and PanSTARRS photometry in M67 and Rup 147 for extinction using the most recent version (Green et al. 2019) of the dustmaps (Green 2018) package that provides 3D dust maps derived from 2MASS and PanSTARRS photometry together with Gaia distances. When no Gaia parallax was available we used the cluster median distance instead. If an extinction value was not available for a given star we used the average extinction value of the respective cluster. We accounted for extinction in Gaia BP and RP bands using the reddening $E(B_P - R_P)$ derived from Gaia photometry and parallax from Gaia DR2 (Andrae et al. 2018). We dropped targets that were too bright and would saturate the detector (Kepler magnitude $K_p \leq 9$).

2.3.1. Effective temperatures T_{eff}

We applied several methods and color-temperature relations (CTR) to determine robust T_{eff} (Figs. 2 and 3). We used CTRs from Boyajian et al. (2013) and Mann et al. (2016) (erratum to Mann et al. 2015), T_{eff} derived from Gaia DR2 using the StarHorse algorithm (Queiroz et al. 2018), and T_{eff} inferred from Gaia DR2 using the Apsis pipeline (Bailer-Jones et al. 2013; Andrae et al. 2018).

Boyajian et al. (2013) determined CTRs from a range of interferometrically characterized stars using $g-r$, $g-i$, $g-z$, $g-J$, $g-H$, and $g-K$ colors from SDSS and Johnson magnitudes for A to K stars. Their sample was centered on solar metallicity, so we constrained the use of these CTRs to stars with $-0.25 < [\text{Fe}/\text{H}] < 0.25$. Following Boyajian et al. (2013), we transformed 2MASS JHK to $J - H$, $H - K$, and $J - K$ in the Johnson system from 2MASS to the Bessell-Brett system (Carpenter 2001), and from Bessell-Brett to Johnson using the relations in Bessell & Brett (1988).

Mann et al. (2015) derived CTRs from absolutely calibrated spectra to which they fitted atmospheric models to obtain T_{eff} . Alternatively, they determined T_{eff} from long-baseline optical interferometry measurements using the bolometric flux. They provided transformations for SDSS/2MASS $r - z$ and $r - J$, or Gaia $BP - RP$ where extra information could be added from metallicity or 2MASS $J - H$. The relations in Mann et al. (2015) were only valid if metallicity was sufficiently close to solar, which was satisfied for the OCs in this paper (see Table 1).

We supplemented our estimates with T_{eff} estimates from Anders et al. (2019) who determined distances, extinctions, and various stellar parameters for 137 million stars in Gaia DR2 using the StarHorse pipeline (Queiroz et al. 2018).

Gaia DR2 published T_{eff} for over 160 million sources (Gaia Collaboration et al. 2018b). The typical uncertainty was quoted at 324 K, but it was lower for stars above ~ 4100 K and below ~ 6700 K, so that we adopt 175 K which is above the quoted root-mean-squared error in this T_{eff} range (Andrae et al. 2018), and use provided values only in this range.

Empirical CTRs suffer from systematic errors that stem both from the different methods applied, and from sample selection biases. We therefore used several empirical relations in their appropriate ranges to obtain T_{eff} from each, and draw a more reliable median value. Targets that were lacking sufficient photometric data to derive T_{eff} , or that were too hot to be expected to have a convective envelope ($T_{\text{eff}} \geq 7000$ K), were removed from the sample. We dropped all targets where the uncertainty on the weighted mean T_{eff} was greater than 10 %. Only targets that were assigned a T_{eff} were searched for flares.

Table 1. Open clusters.

| | d [pc] | stars | LCs | flares | campaigns | age [Myr] | [Fe/H] |
|----------|--------|-------|------|--------|-------------|--|-------------|
| Pleiades | 135.6 | 741 | 741 | 1583 | 4 | 135 (²⁵ / ₂₅) | -0.04(0.03) |
| Hyades | 46.0 | 170 | 179 | 402 | , 4, 13 | 690 (¹⁶⁰ / ₁₀₀) | 0.13(0.02) |
| Praesepe | 185.5 | 913 | 1965 | 1849 | , 5, 16, 18 | 750 (³ / ₇) | 0.16(0.00) |
| Rup 147 | 305.0 | 53 | 53 | 9 | 7 | 2650 (³⁸⁰ / ₃₈₀) | 0.08(0.07) |
| M67 | 908.0 | 234 | 497 | 1 | , 5, 16, 18 | 3639 (¹⁷ / ₁₇) | -0.10(0.08) |

Notes. The values for age, [Fe/H], and distance d are approximate values arrived at by a comparison of existing literature (see Table B.1 in the Appendix). The uncertainties are noted in parentheses. "stars" denotes the number of cluster members with membership probability $p > 0.8$. "LCs" and "campaigns" are the numbers of available light curves, and the K2 campaigns during which they were observed, respectively. "flares" is the number of confirmed flares found in each cluster.

2.3.2. Stellar radii

We used a catalog of empirically characterized stars (Yee et al. 2017) and empirical $T_{\text{eff}} - R_*$ relations derived by Mann et al. (2015, 2016) to obtain R_* from the T_{eff} for the stars in our sample (Fig. 4). Yee et al. (2017) compiled 404 stars with high-resolution spectra from the literature, and performed their own observations of mid to late K-dwarfs, achieving a coverage of low mass stars from 7000 K down to 3000 K. For these stars, the resulting catalog was accurate to 100 K in T_{eff} , 15 % in R_* , and 0.09 dex in [Fe/H]. We interpolated between stars from the catalog to our derived T_{eff} , and propagated the resulting scatter to the uncertainty in R_* if $T_{\text{eff}} > 3500$ K. For stars with $T_{\text{eff}} < 3500$ K we used $T_{\text{eff}} - R_*$ relations derived by Mann et al. (2015, 2016).

2.3.3. Stellar spectra and luminosities

We assigned spectra to our targets from the SpecMatchEmp (Yee et al. 2017) and the FlareSpecPhot libraries (Kirkpatrick et al. 2010; Burgasser et al. 2007, 2008, 2010, 2004; Cruz et al. 2004; Burgasser & McElwain 2006; Rayner et al. 2009; Doi et al. 2010; Filippazzo et al. 2015; Cruz et al. 2003; West et al. 2011; Bochanski et al. 2010, 2007; Schmidt et al. 2010, 2015, 2014; Schmidt 2014; Mann et al. 2015). When a spectrum was available for the derived spectral type in FlareSpecPhot, we preferred it over SpecMatchEmp, which was the case for all stars cooler than M0, where we mapped spectral type to effective temperature (Pecaut & Mamajek 2013). We then combined stellar radii R_* , T_{eff} , and spectra to projected bolometric luminosities $L_{\text{bol},*}$, and projected luminosities in the Kepler band $L_{\text{Kp},*}$ (Shibayama et al. 2013; PaperI). Uncertainties on $L_{\text{Kp},*}$ ranged from 9 % to 52 % with a median value of 17 %.

3. Methods

We detected flare candidates automatically with the AltaiPony software, and validated them by eye. The flare rates are believed to follow a power law distribution that spans multiple orders of magnitude in energy. We fitted both power law parameters simultaneously using the Markov Chain Monte Carlo method to sample from the posterior distribution.

3.1. Flare finding

We used the open source software AltaiPony² to automatically detect and characterize flares in our sample. The code base

relied on K2SC³ (Aigrain et al. 2016) to remove instrumental and astrophysical variability from K2 light curves. We did not use the de-trended light curves available in MAST⁴, but used K2SC to de-trend light curves from the re-processed final data release. We clipped outliers at 3σ iteratively, as compared to the original work, where outliers were clipped at 5σ (Aigrain et al. 2016). We also masked \sqrt{n} data points before and after the sequences of outliers with lengths $n > 1$, because these regions often showed physically elevated flux levels below the 3σ threshold.

After de-trending, the flare finder algorithm searched for continuous observing periods, defined as time series that were longer than 10 data points at a minimum cadence of 2 h. All further routines were run on these observing periods. We estimated the scatter in the residual flux using a rolling standard deviation with a 7.5 h window excluding the outliers.

In the next step, the finder iteratively clipped excursions from the median value at 3σ . After each iteration, outliers were replaced with the last median value. Either after convergence, or 50 iterations, the resulting median value was adopted.

The previously masked outliers in the light curve were assigned the mean uncertainty from the remainder of the light curve. Thus we used the non-flaring parts of the light curve to define the scatter in the flaring parts. This procedure assumed that the scatter of the 80 day light curve was stable throughout the observation. In K2, stability could not be guaranteed, leading to false positive detections in regions of light curves where the uncertainty was underestimated due to strong systematic effects that K2SC could not compensate. These false positives were later removed manually.

Using the iteratively derived median as quiescent flux and the estimated scatter, we flagged all outliers above 3σ in the residual light curve. For flare candidates, we required at least three consecutive data points to fulfill the 3σ -criterion. We merged the candidates into single candidate events if they were less than four data points apart.

The Kepler flare sample has shown to be difficult to treat in a fully automated way. Without manual vetting, the event samples remained significantly contaminated (Yang & Liu 2019). As K2 was subject to severe technical difficulties, we expected that the contamination would be even higher. Out of 6916 only 3844 could be confirmed. Some light curves could not be de-trended using K2SC alone. Light curves with extreme astrophysical signal like deep transits, rotational modulation on time scales of

³ github.com/0xES/k2sc

⁴ archive.stsci.edu/prepds/k2sc/

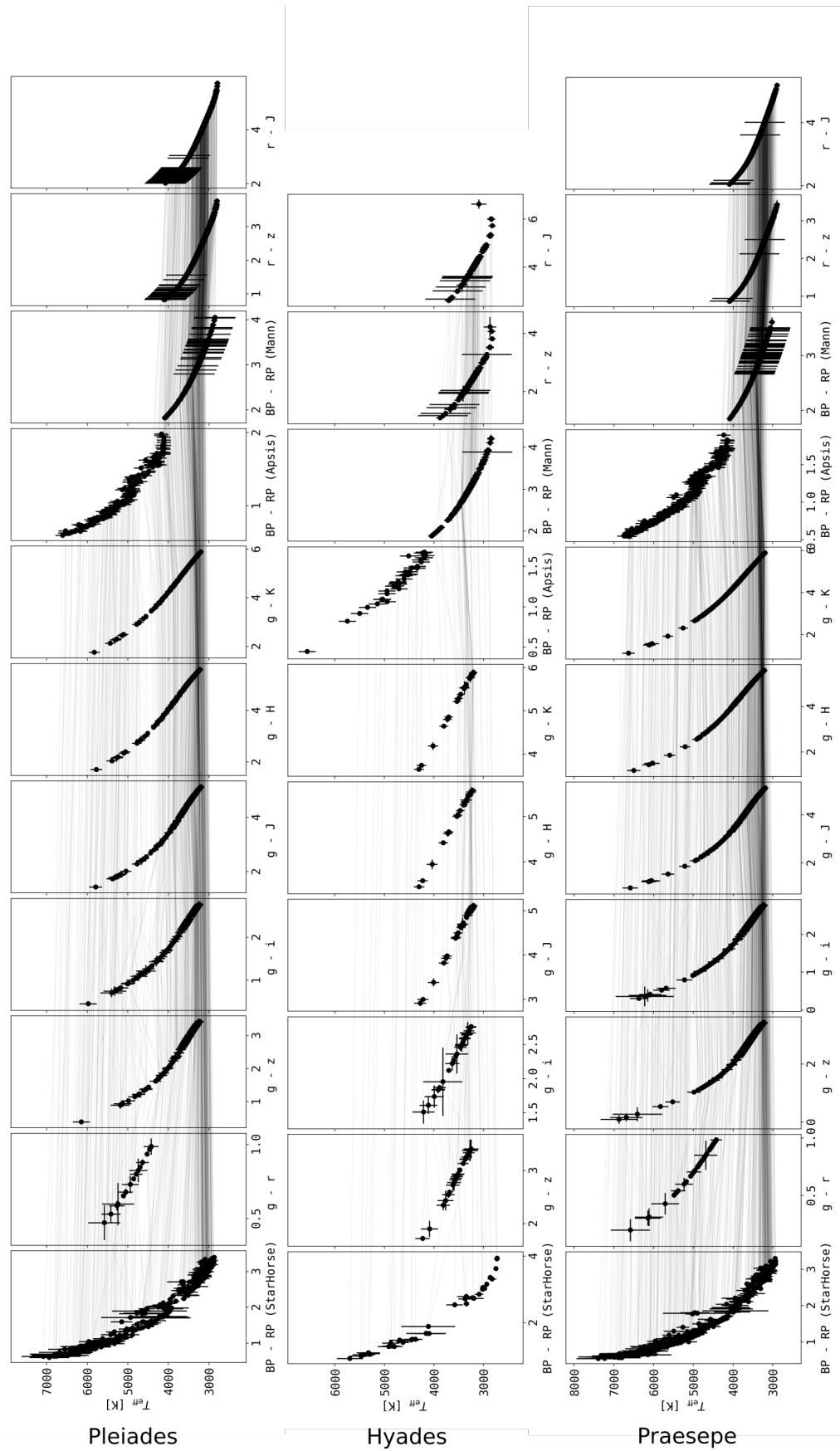


Fig. 2. Empirical color- T_{eff} relations applied to high probability members of the Pleiades, the Hyades, and Praesepe. Individual stars are connected by lines between sub-plots to illustrate differences in the relations. We used PanSTARRS griz, 2MASS JHK, and Gaia DR2 BP and RP photometry with the following relations: $BP - RP$ (StarHorse, Anders et al. 2019); $g - r$, $g - i$, $g - z$, $g - J$, $g - H$, $g - K$ (Boyajian et al. 2013); $BP - RP$ (Apsis, Andrae et al. 2018); $BP - RP$ (Mann), $r - z$, and $r - J$ (Mann et al. 2016).

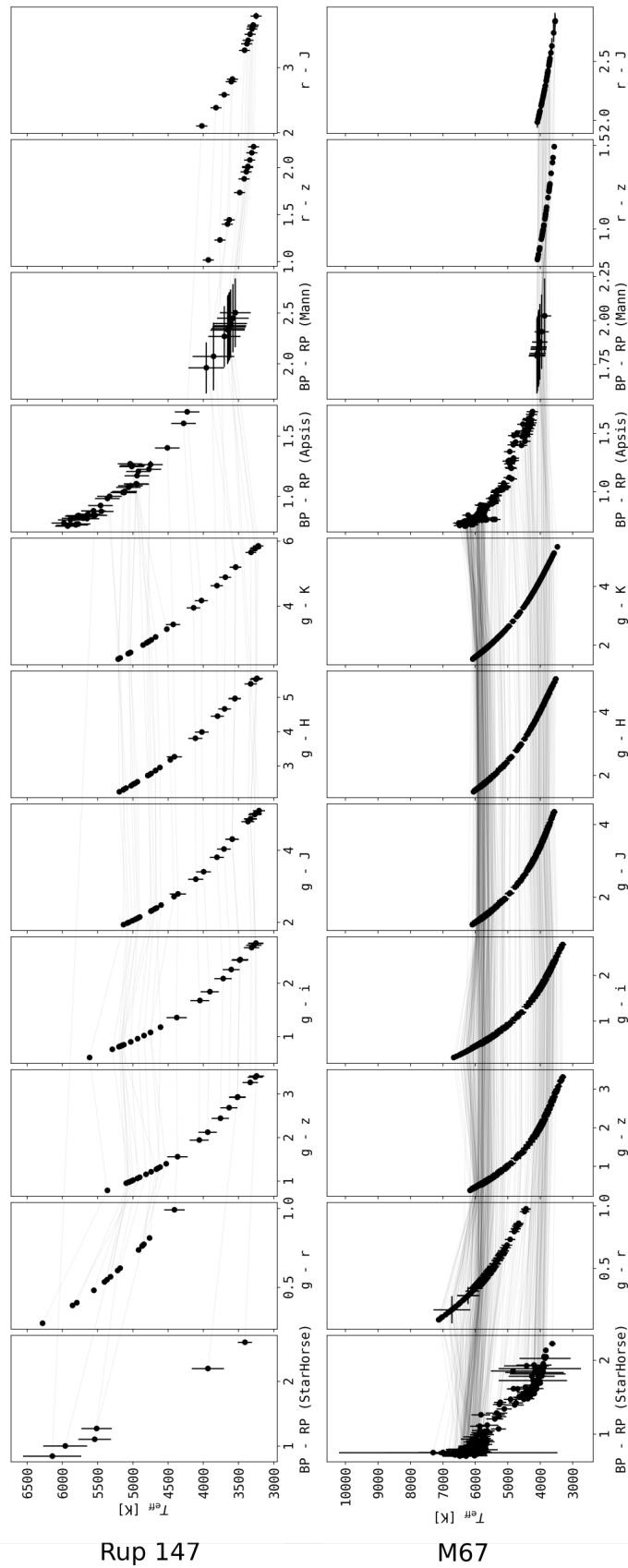


Fig. 3. Empirical color- T_{eff} relations applied to high probability members of Rup 147, and M67. See Fig. 2 for details.

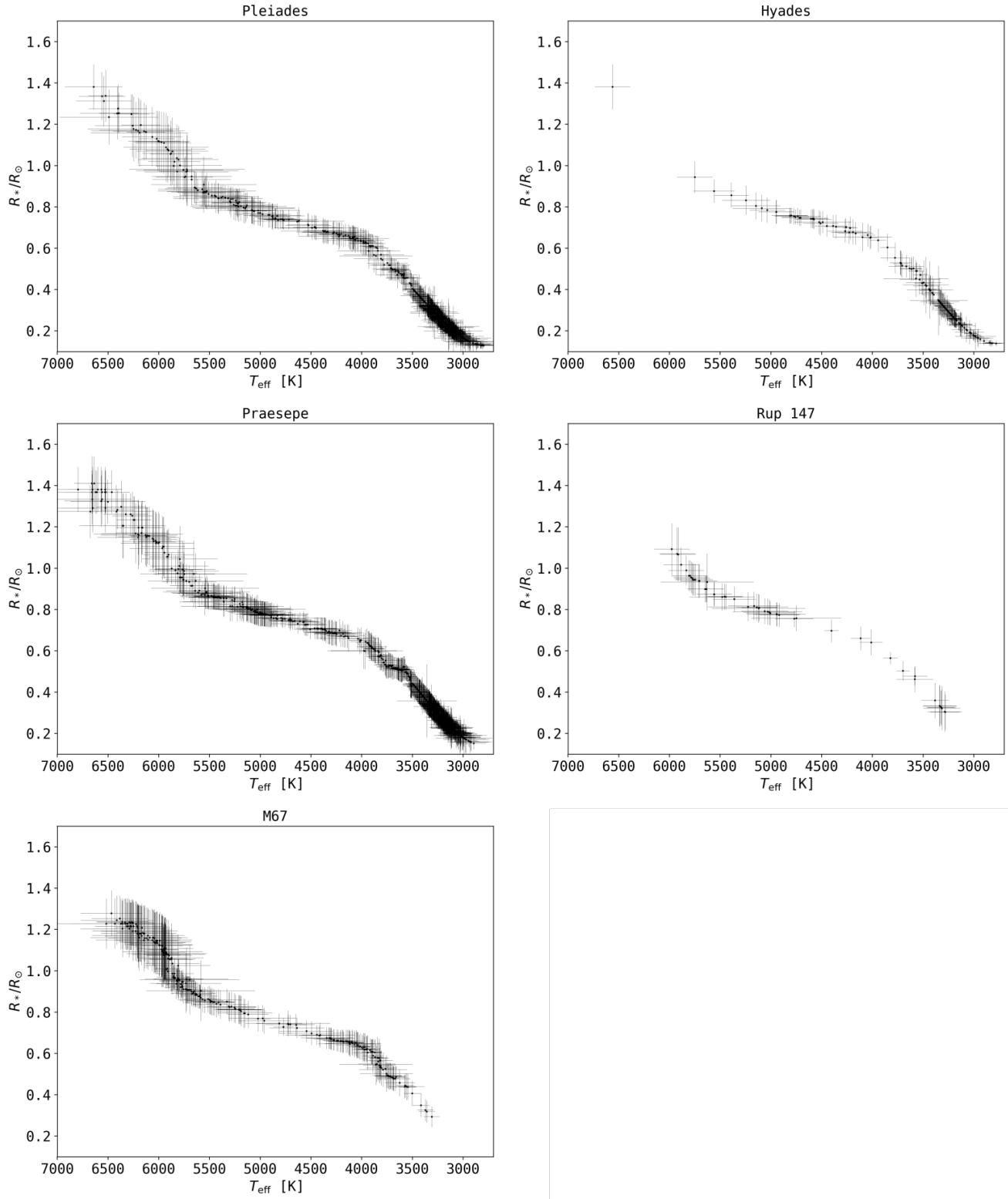


Fig. 4. $T_{\text{eff}} - R_*$ distributions for all clusters in this study. Each panel shows the distribution of high probability members of the OC indicated in the panel title. Stellar radii R_* are given in units of solar radii. Uncertainties on T_{eff} and R_* (grey error bars) were propagated from the photometry, the color- T_{eff} relations, and empirical $T_{\text{eff}} - R_*$ relations.

a few hours or passages of bright solar system objects (SSO) had to be masked or fitted with an additional sinusoidal component to the K2SC-treated time series. **Other SSOs mimicked the fast rise and exponential decay shape of flares, and could only be identified using an extension to the Virtual Observatory (VO) tool sky body tracker (SkyBoT, Berthier et al. 2006; Berthier et al. 2016). We identified 144 SSOs using SkyBot and visual inspection with lightkurve (Lightkurve Collaboration et al. 2018), that is 3.6 % of all confirmed flare candidates (see Appendix D).** A number of light curves were excluded from the flare search because they saturated the detector, or because the target aperture overlapped with broken pixels. Some very faint targets and extreme variables could not be searched because the de-trending did not terminate successfully. The online version of the final flare sample (Table 2) includes explanatory flags and notes on the excluded targets.

3.2. Equivalent duration ED

For each candidate, flaring time, amplitude and equivalent duration (ED) were returned. ED is the area between the LC and the quiescent flux, that is, the integrated flare flux divided by the median quiescent flux F_0 of the star, integrated over the flare duration (Gershberg 1972):

$$ED = \int dt \frac{F_{\text{flare}}(t)}{F_0}. \quad (1)$$

ED is a quantity independent of calibration and distance that is suited to compare flaring activity on stars where these properties are uncertain. ED describes the time during which the non-flaring star releases as much energy as the flare itself. This time can be shorter or longer than the actual flare duration. The uncertainty in ED depended on the light curve noise properties, time sampling, spacecraft roll, and other systematic effects. Moreover, K2SC de-trending and the flare finding procedure introduced additional uncertainty that dominated the photometric noise.

3.3. Kepler flare energy E_{Kp}

Multiband time-resolved observations of active M dwarfs have shown that continuum flux accounts for the majority of the energy radiated by flares (Kowalski et al. 2013). The effective temperature of this blackbody, however, varies: While solar flares are relatively cool, with $T_{\text{eff}} \approx 5000 - 7000$ K (Kleint et al. 2016; Kerr & Fletcher 2014; Watanabe et al. 2013; Namekata et al. 2017). Most stellar events emit in the blue, and exhibit temperatures of about 9 000 – 10 000 K (Hawley & Fisher 1992b; Kretzschmar 2011; Davenport et al. 2012; Shibayama et al. 2013). However, at least one M dwarf flare reached 40 000 K as seen in FUV spectra (Froning et al. 2019). A dependence of flare temperature on stellar age, or mass, or both, will enter our analysis if we quantify bolometric flare energy. At about 6 200 K, the Kepler pass band captures the largest flux fraction, at 10 000 K 72 %, at 40 000 K only 4% of this value is transmitted. Given the uncertainties on stellar luminosity in the Kepler band (see Sec. 2.3.3) and on ED , the resulting flare energies (PaperI)

$$E_{Kp} = L_{Kp,*} \cdot ED \quad (2)$$

will substantially deviate from the true released energy. If these uncertainties did not affect all flares in a similar fashion, the present analysis will have suffered from non-uniform biases that

affected the flare frequency distributions on stars of different ages and temperatures, and skewed the flare distributions within each subsample. However, the comparison to other studies (see Sec. 5.1) suggested that our results were mostly consistent with studies based on similar data (see Fig. 11, and Lin et al. 2019 therein for an example), although they used different methods to infer E_{flare} .

3.4. Power law fits

Flare frequency distributions (FFDs) follow power law relations that cover several orders of magnitude, from solar microflares to stellar superflares (see Fig. 9 in Shibayama et al. 2013). In the cumulative distribution the frequency $f(> E)$ of flares above a certain energy E is

$$f(> E) = \frac{\beta}{\alpha - 1} E^{-\alpha+1}, \quad (3)$$

and, analogously, for ED (Gershberg 1972). We used and compared two approaches to fitting α and β to the data. The first was a Modified Maximum Likelihood Estimator (MMLE) for power law distributions (Maschberger & Kroupa 2009). The second approach was more specifically tailored to flaring activity. **We used the MCMC method to sample from the predictive distribution for a source that produced flares that followed a Poisson process in time. These flares' energies were also required to be power law distributed by the model (Wheatland 2004).** While the MMLE was computationally efficient and was useful to obtain first results (see Appendix E), only the predictive distribution allowed us to fit for α and β simultaneously, and determine their uncertainties.

The posterior distribution in Wheatland (2004) captured both the Poissonian distribution of flare events in time, and their power law distribution in energy, simultaneously. The authors derived this model to be able to predict the flaring rate above a given energy for any active region on the Sun including changes in flaring activity rates as the active region evolves, and also characteristics of the active region itself, such as sunspot classifiers. In our simplification of the model, we assumed that the flare generating process did not change within the observation time span in any star in our sample ($M = M'$ in Eq. 24 in Wheatland 2004). Another assumption was that this process was the same for all stars in the sample ($\Lambda_{MC} = 1$ in aforementioned Eq. 24). Under these assumptions the samples of flares found in the light curves of different stars and light curves obtained during different campaigns could be stacked together. With these simplifications to Eq. 24, we defined the joint posterior distribution for the probability ϵ that a flare with ED or E_{Kp} above some value S_2 would occur within a time period ΔT :

$$\begin{aligned} p(\epsilon, \alpha) = & C \cdot (-\ln(1 - \epsilon))^M \\ & \cdot (\alpha - 1)^M \cdot \Gamma(\alpha) \left[\frac{(S_2/S_1)^{M+1}}{\pi} \right]^{\alpha} \\ & \cdot (1 - \epsilon)^{(T/\Delta T) \cdot (S_2/S_1)^{\alpha-1}-1}. \end{aligned} \quad (4)$$

C was the normalisation constant, M was the number of events, T the total observation time. Γ contained the prior distribution for α , and S_1 denoted the detection threshold above which all flares were detected. π encapsulated the flare energies as

$$\pi = \prod_{i=1}^M \frac{s_i}{S_1}, \quad (5)$$

where $\{s_1, s_2, \dots, s_m\}$ were the flare energies E_{Kp} or ED .

From the posterior distribution of ϵ we derived β by combining Poisson statistics

$$\epsilon = 1 - e^{(-f \cdot \Delta T)} \quad (6)$$

and the cumulative power law function in Eq. 3:

$$\beta = -\frac{\ln(1 - \epsilon) \cdot (\alpha - 1)}{\Delta T} \cdot S_2^{\alpha-1} \quad (7)$$

With a uniform prior for α the results from the MMLE and Markov Chain Monte Carlo (MCMC) sampling from the posterior distribution were consistent within uncertainties (see Appendix E). However, the MCMC method allowed us to fit for both ϵ and α simultaneously, and to use more informative priors. The power law exponent determined for flare frequency distributions has consistently been found to be independent of age (Davenport et al. 2019), and spectral type for solar-type and low mass dwarfs (see Fig. G.1 in Appendix G). We chose our prior to reflect this result: Starting from a uniform prior for α and ϵ , we found a Gaussian distribution to be an excellent fit to the posterior distribution for α for the full sample of flares in E_{Kp} and ED space. We then used this Gaussian distribution as a prior for the FFDs in individual age and T_{eff} bins.

4. Results

The core objective of this work was to quantify how the previously noted decline in flaring activity with age would unfold for different spectral types. To this end, we searched the long cadence light curves of stars across a broad range of spectral types in five different OCs for flares, and measured their energies and occurrence rates. **We found 3844 flares in five OCs for T_{eff} between 2500 K and 6000 K. The flares' amplitudes a , start and end cadence numbers c_0 and c_1 , ED , energies E_{Kp} , along with the stars' EPIC ID, T_{eff} , and bolometric and Kepler band luminosities $L_{bol,*}$ and $L_{Kp,*}$ are listed in Table 2. We fitted power law relations to the flare frequency distributions (FFD) of stars binned by age, and T_{eff} (Figs. 6, 7 and Table 3).** We found that flaring activity decreased with increasing age from ZAMS to 3.6 Gyr, and from mid-M to G dwarfs. Except for the stars in the coolest temperature bin (M5.5–M8, 2500–3000 K), stellar flaring activity at a given age was higher for cooler stars.

4.1. Flare frequency distributions

We fitted power law parameters α and β (Eq. 3) to the full sample FFDs in E_{Kp} and ED space by sampling from the joint posterior distribution (Eq. 4), where we chose uninformative priors for both α and ϵ . The detection threshold in any FFD was not a unique function of E_{Kp} or ED , but depended on the flares' amplitudes and durations. Since it was computationally not feasible to perform the injection and recovery of synthetic flares to determine the effect of K2SC de-trending, we could not correct for the incompleteness of flare detection at the low energy end. Our approximation to the detection threshold was to use only the portion of the FFD for the fit, where all flaring stars contributed. For the full sample fits (Fig. 5) we doubled this energy threshold. This mitigated but did not solve the problem of a detection probability < 1 that still affected the shape of the FFDs at the lower energy end. We did not exclude even more flares on the low-energy end because it would have given increasing weight to the high-energy tail

naturally suffered from low numbers of flares. In the case of the full sample we expected that for some stars the high-energy threshold would be reached at some energy below the maximum detected energy in the sample. The co-adding of flare samples from stars of vastly different activity levels aggravated the high-energy incompleteness. Consequently the high-energy tail of the FFD was also incomplete. The absolute value of α obtained in this study should be interpreted in light of these limitations. It remained useful as a relative anchor for the comparison within the sample assuming that the FFDs for different age and T_{eff} bins suffered from the same incompletenesses.

We fitted a Gaussian distribution to the posterior distribution for α from the full sample. The values for the full sample FFDs in E_{Kp} and ED space (Fig. 5) are summarized in Table 4. **In the table, α and β are the power law parameters from Eq. 3. The number of flares n_{tot} in the distribution is higher than the number n_{fit} of flares used to fit the power law because we omitted the low-energy tail of the distribution.**

The core part of this work was to investigate the effects of age on the flaring activity for low mass stars. We therefore split up the full sample into T_{eff} bins and constructed the FFDs cluster by cluster (Figs. 6 and 7). **The full sample posteriors for α were then used as priors for the power law fits to the FFDs in the individual bins. The power law fit parameters to these FFDs, broken down by cluster and T_{eff} , are summarized in Table 3. The indices s and erg to α and β indicate the fits to the FFDs in ED and E_{Kp} , respectively. n is the number of flares detected in each T_{eff} bin.**

4.2. β_s

Relative flaring activity levels were best described by β_s , the power law fit intercept for the FFDs in ED space (R_{1s} in Davenport et al. 2019). Because of the definition of ED (Eq. 1) β_s is a measure of flaring activity in which the different energy budgets of stars are controlled for. We could therefore use β_s to compare across both T_{eff} and age at the same time. Fig. 8 can also be interpreted as a synthesis of the FFDs presented in Fig. 6. Overall, β_s declined with age in all investigated T_{eff} bins but the 2500 – 3000 K bin, where it increased from ZAMS to Hyades age. This reverse was also present in a K2 short cadence K7–M6 dwarf flaring study (Raetz et al. 2020). In the lowest mass bin (M5–M6) the authors measured higher flaring activity for relatively slow rotators ($P_{\text{rot}} > 2$ d) than for their fast counterparts ($P_{\text{rot}} < 2$ d).

Lurie et al. (2015) analysed the flares on GJ 1245 A and B, two M5 dwarfs in a triple system with another M8 dwarf, that were observed in 1-min cadence during the original Kepler mission. GJ 1245 A and B both fell roughly into the 3000 – 3250 K bin. From their FFDs and fitted values for α for each component we inferred $\beta_{s,A} \approx 1900 \text{ yr}^{-1}$ and $\beta_{s,B} \approx 2200 \text{ yr}^{-1}$, consistent with β_s for the Pleiades, or Hyades/Praesepe within uncertainties.

4.3. Flaring luminosity FA

We can relate the luminosity in flares in the Kepler band to the quiescent bolometric luminosity of the star, and by this define the fractional flare luminosity FA (similar to PaperI):

$$FA = \frac{E_{Kp,\text{flare,tot},*}}{t \cdot L_{bol,*}} \quad (8)$$

We determined $L_{bol,*}$ from R_* and T_{eff} , as described in Sec. 2.3. The energy released in flares was inferred using our derived

Table 2. Confirmed flare candidates detected in open cluster stars observed by K2, sorted by amplitude a .

| EPIC | C | cluster | c_0 | c_1 | a | T_{eff} [K] | ED [s] | $L_{\text{bol},*}$ [erg/s] | L_{Kp} [erg/s] |
|-----------|----|----------|--------|--------|-----------|----------------------|------------|----------------------------|-------------------------|
| 211079830 | 4 | Pleiades | 105984 | 105993 | 15.330194 | 3097(87) | 63340(63) | 8.29(3.34) 10^{29} | 3.32(1.34) 10^{29} |
| 210720772 | 4 | Pleiades | 107181 | 107184 | 9.674757 | 3104(86) | 19901(7) | 8.66(3.45) 10^{29} | 3.48(1.38) 10^{29} |
| 247523445 | 13 | Hyades | 143106 | 143109 | 8.260956 | 2964(49) | 16615(11) | 4.33(1.09) 10^{29} | 1.69(0.43) 10^{29} |
| 212021131 | 5 | Praesepe | 108974 | 108980 | 7.421916 | 3215(68) | 19828(175) | 2.01(0.65) 10^{30} | 8.22(2.65) 10^{29} |
| 210978953 | 4 | Pleiades | 106762 | 106770 | 6.769888 | 3050(95) | 39467(125) | 6.20(2.63) 10^{29} | 2.46(1.04) 10^{29} |
| 211913613 | 16 | Praesepe | 156845 | 156849 | 6.690356 | 3218(66) | 21632(147) | 2.05(0.65) 10^{30} | 8.37(2.63) 10^{29} |
| 211127297 | 4 | Pleiades | 106754 | 106759 | 6.449569 | 3147(86) | 20830(5) | 1.13(0.45) 10^{30} | 4.59(1.81) 10^{29} |
| 211681193 | 5 | Praesepe | 108116 | 108120 | 5.570804 | 3182(76) | 11198(95) | 1.64(0.58) 10^{30} | 6.68(2.37) 10^{29} |
| 211024798 | 4 | Pleiades | 104822 | 104826 | 5.394897 | 3290(62) | 12524(63) | 2.58(0.75) 10^{30} | 1.06(0.31) 10^{30} |
| 211134185 | 4 | Pleiades | 103891 | 103896 | 4.951629 | 3127(96) | 17459(33) | 9.99(4.33) 10^{29} | 4.03(1.75) 10^{29} |
| 211095280 | 4 | Pleiades | 106283 | 106287 | 4.796979 | 3138(93) | 12186(10) | 1.06(0.45) 10^{30} | 4.32(1.82) 10^{29} |
| 211022535 | 4 | Pleiades | 104262 | 104267 | 3.994973 | 2953(76) | 15164(57) | 3.50(1.10) 10^{29} | 1.37(0.43) 10^{29} |
| 211010517 | 4 | Pleiades | 106680 | 106685 | 3.968907 | 3252(70) | 16241(171) | 2.09(0.68) 10^{30} | 8.59(2.77) 10^{29} |
| 210846442 | 4 | Pleiades | 104410 | 104415 | 3.959977 | 3311(79) | 13515(10) | 2.88(0.96) 10^{30} | 1.18(0.40) 10^{30} |
| 212017838 | 5 | Praesepe | 111183 | 111192 | 3.671037 | 3307(89) | 10274(10) | 3.35(1.22) 10^{30} | 1.38(0.50) 10^{30} |
| 211984058 | 5 | Praesepe | 109952 | 109965 | 3.320636 | 3124(97) | 16063(149) | 1.17(0.51) 10^{30} | 4.73(2.06) 10^{29} |
| 211912899 | 5 | Praesepe | 110700 | 110706 | 3.257997 | 3133(81) | 7967(16) | 1.24(0.47) 10^{30} | 5.01(1.89) 10^{29} |
| 211151674 | 4 | Pleiades | 106457 | 106467 | 3.166323 | 3072(93) | 17843(106) | 7.10(2.99) 10^{29} | 2.84(1.19) 10^{29} |
| 211822895 | 5 | Praesepe | 107809 | 107812 | 3.164494 | 3005(177) | 6883(31) | 5.68(3.98) 10^{29} | 2.25(1.57) 10^{29} |
| 211760567 | 5 | Praesepe | 109962 | 109965 | 3.061417 | 3245(58) | 7838(9) | 2.39(0.69) 10^{30} | 9.84(2.83) 10^{29} |
| 211939350 | 16 | Praesepe | 155018 | 155022 | 2.892939 | 3149(150) | 9542(68) | 1.36(0.86) 10^{30} | 5.52(3.49) 10^{29} |
| 211137806 | 4 | Hyades | 106768 | 106775 | 2.482828 | 3127(58) | 9208(8) | 1.16(0.35) 10^{30} | 4.69(1.40) 10^{29} |
| 210674207 | 13 | Hyades | 141708 | 141711 | 2.419586 | 3210(74) | 5343(3) | 1.90(0.65) 10^{30} | 7.78(2.66) 10^{29} |
| 211949410 | 5 | Praesepe | 109858 | 109864 | 2.401426 | 3325(95) | 7807(14) | 3.71(1.40) 10^{30} | 1.53(0.58) 10^{30} |
| 211010517 | 4 | Pleiades | 106561 | 106564 | 2.341076 | 3252(70) | 4838(36) | 2.09(0.68) 10^{30} | 8.59(2.77) 10^{29} |
| 211984058 | 5 | Praesepe | 108584 | 108587 | 2.155468 | 3124(97) | 4817(13) | 1.17(0.51) 10^{30} | 4.73(2.06) 10^{29} |
| 211983544 | 18 | Praesepe | 162792 | 162798 | 2.096077 | 3159(98) | 6924(55) | 1.44(0.63) 10^{30} | 5.88(2.55) 10^{29} |
| 210988354 | 4 | Pleiades | 106012 | 106017 | 2.057812 | 3661(144) | 5725(1) | 1.40(0.31) 10^{31} | 6.06(1.32) 10^{30} |
| 210886447 | 4 | Pleiades | 103871 | 103877 | 2.057490 | 3048(105) | 8710(49) | 6.13(2.83) 10^{29} | 2.43(1.12) 10^{29} |
| 211098921 | 4 | Pleiades | 105254 | 105262 | 2.041041 | 3300(101) | 7499(5) | 2.72(1.10) 10^{30} | 1.12(0.45) 10^{30} |

Notes. The full table is available via CDS. See Section 4 for explanations on the columns. Uncertainties are given in parentheses.

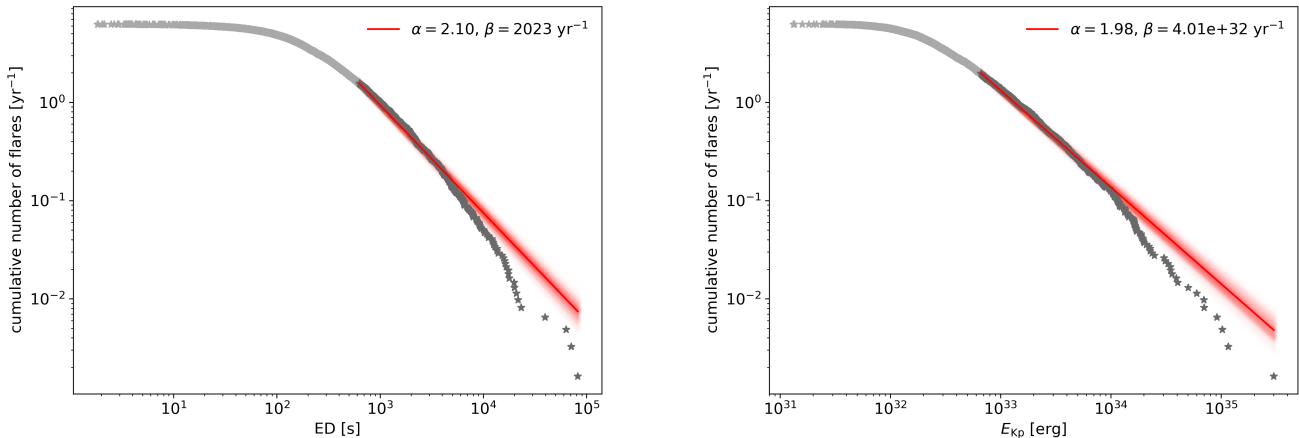


Fig. 5. Cumulative flare frequency distributions (FFD, grey stars) in ED (left panel) and E_{Kp} (right panel) with respective power law fits (red lines) to the full sample of confirmed flare candidates. The complete distribution (light grey stars) is larger than the portion used for the fit (dark grey stars) because we omitted the incomplete low energy tail. The red shade consists of a randomly drawn sample from the posterior distribution. α and β are the best fit power law parameters as defined in Eq. 3.

stellar luminosities. It declines with age for every T_{eff} bin considered for both the total luminosity and relative to the quiescent flux (Fig. 9). However, we found that FA remained high ($> 10^{-5}$) in early to mid M dwarfs for several hundred Myr after Pleiades age.

4.4. Hyades and Praesepe: Rotating differently

We expected the flaring activity in the Hyades and Praesepe to be very similar because they were nearly coeval clusters with ages around 700 Myr, and comparable metallicities ([Fe/H](Praesepe) = 0.16, [Fe/H](Hyades) = 0.13, Netopil et al. 2016). We found this reflected in all our FFDs, except for the

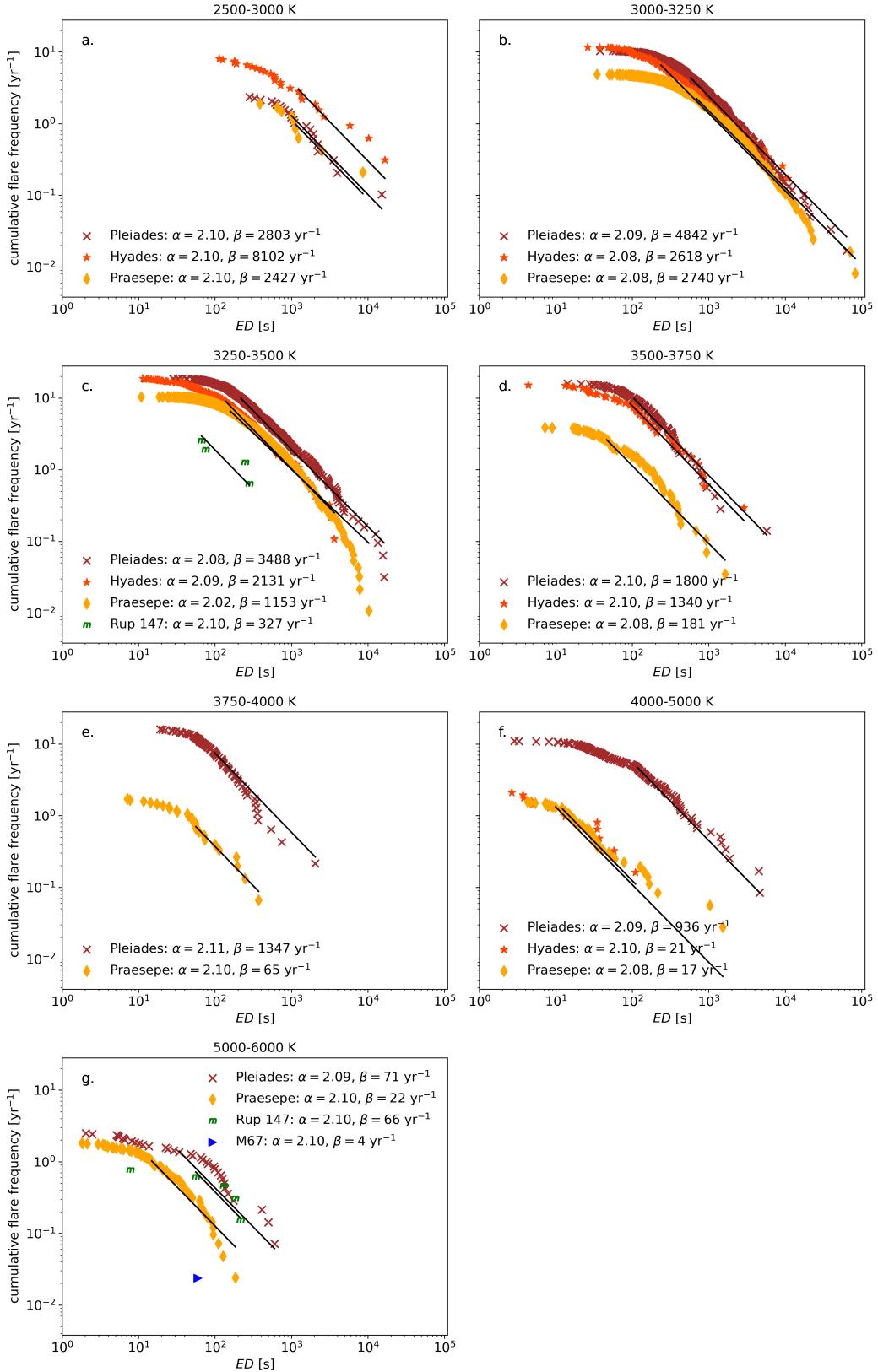


Fig. 6. Cumulative flare frequency distributions (FFD, scatter) in ED , and respective power law fits (black lines), in log-log representation. In each of the panels a-g. the distributions of flares are shown for different OCs for samples of stars in the T_{eff} bin that is given in the panel title. The different clusters are the Pleiades (maroon crosses), the Hyades (orange stars), Praesepe (yellow diamonds), Rup 147 (green "m"s), and M67 (blue triangles). The legends denote the best fit power law exponent α , and intercept β (Eq. 3) for each distribution. We used the fit to the full sample as a prior for α . Higher β indicate higher flare frequencies. The extension of the black lines in ED indicates the low-energy threshold adopted for every fit. For the single flare detection in M67 we give the power law parameters obtained directly from Eq. 3 using the prior value for α . When no distribution is shown, either no flares were found in the sub-sample, or no stars in that T_{eff} bin were observed by K2. The overview of all power law fit parameters including uncertainties is given in Table 3.

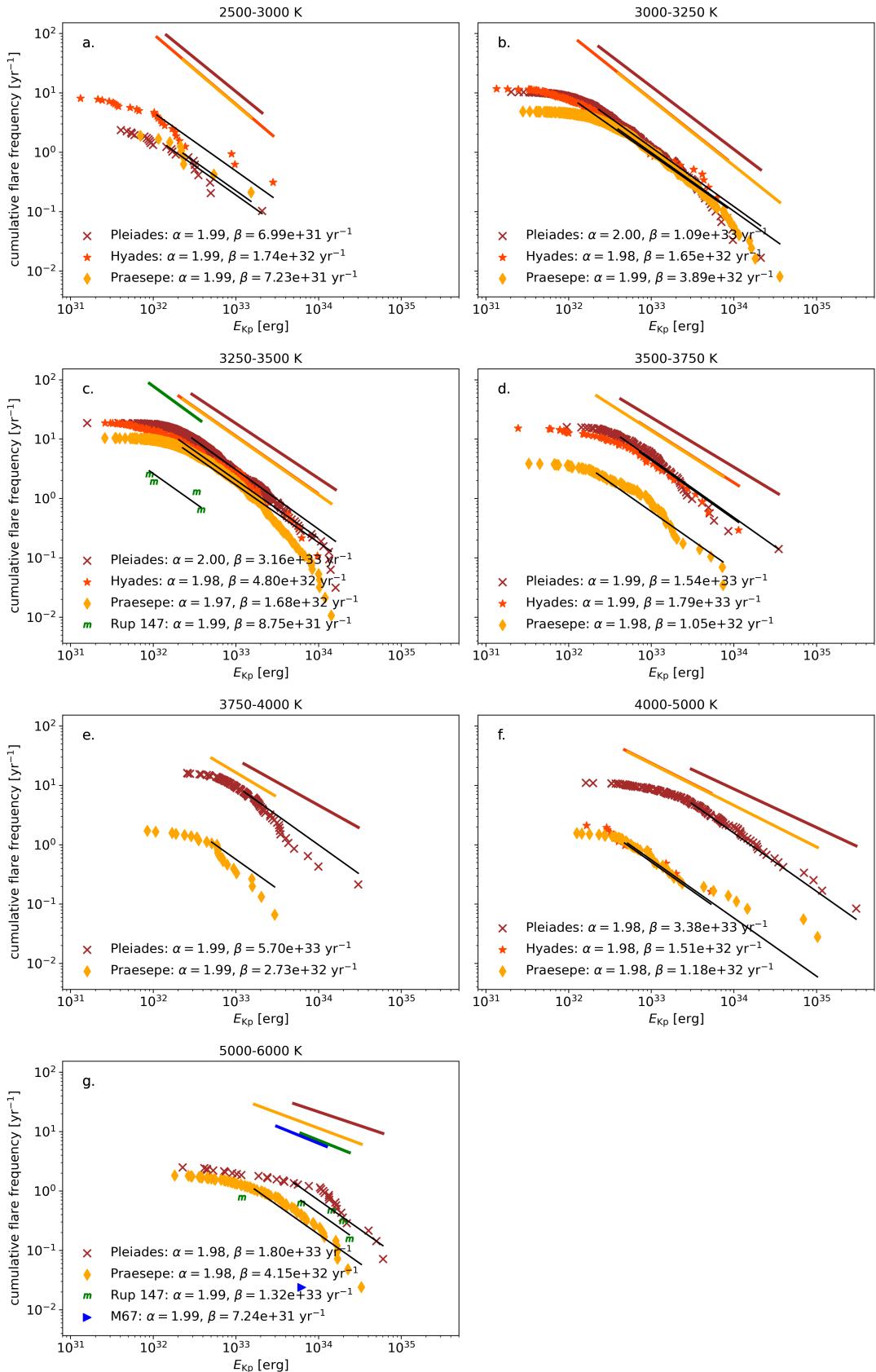


Fig. 7. Same as in Fig. 6 but for E_{Kp} instead of ED . Additionally, predictions from the Davenport et al. (2019) gyrochronology-calibrated FFD parametrization with stellar age and mass were added in the colors that denote the different OCs (see discussion in Sec. 5.2). We used the mean of each T_{eff} bin to determine the mass (Pecaut & Mamajek 2013), and OC ages from the literature.

Table 3. Power law fit parameters α and β for all clusters and T_{eff} bins in E_{Kp} and ED FFDs.

| T_{eff} [K] | cluster | a_s | β_s [yr^{-1}] | ED_{\min} [s] | ED_{\max} [s] | $n_{\text{tot},s}$ | $n_{\text{fit},s}$ | α_{erg} | β_{erg} [yr^{-1}] | $E_{\text{Kp},\min}$ [erg] | $E_{\text{Kp},\max}$ [erg] | $n_{\text{tot},\text{erg}}$ | $n_{\text{fit},\text{erg}}$ |
|----------------------|----------|------------------------|--|------------------------|------------------------|--------------------|--------------------|------------------------|---|----------------------------|----------------------------|-----------------------------|-----------------------------|
| 2500-3000 | Hyades | 2.10 _(0.03) | 8102 ₍₄₂₀₁₎ 2853 ₍₂₈₅₃₎ | 1.24 · 10 ³ | 1.66 · 10 ⁴ | 26 | 9 | 1.99 _(0.03) | 1.7 _(1.5) · 10 ³² | 1.11 · 10 ³² | 2.82 · 10 ³³ | 26 | 13 |
| | Pleiades | 2.10 _(0.03) | 2803 ₍₁₂₉₀₎ 916 ₍₉₁₆₎ | 0.99 · 10 ³ | 1.52 · 10 ⁴ | 23 | 12 | 1.99 _(0.03) | 0.7 _(0.6) · 10 ³² | 1.45 · 10 ³² | 2.08 · 10 ³³ | 23 | 12 |
| 3000-3250 | Praesepe | 2.10 _(0.03) | 2427 ₍₁₀₄₃₎ 1588 ₍₁₅₈₈₎ | 1.13 · 10 ³ | 0.86 · 10 ⁴ | 9 | 4 | 1.99 _(0.03) | 0.7 _(0.6) · 10 ³² | 2.3 · 10 ³² | 1.53 · 10 ³³ | 9 | 4 |
| | Hyades | 2.08 _(0.03) | 2618 ₍₇₀₉₎ 570 ₍₅₇₀₎ | 2.37 · 10 ² | 1.29 · 10 ⁴ | 137 | 76 | 1.98 _(0.03) | 1.6 _(1.4) · 10 ³² | 1.31 · 10 ³² | 0.84 · 10 ³⁴ | 137 | 78 |
| 3250-3500 | Pleiades | 2.09 _(0.03) | 4842 ₍₁₀₁₁₎ 1262 ₍₁₂₆₂₎ | 0.58 · 10 ³ | 0.63 · 10 ⁵ | 616 | 258 | 2.00 _(0.03) | 1.1 _(0.9) · 10 ³³ | 2.32 · 10 ³² | 2.11 · 10 ³⁴ | 616 | 311 |
| | Praesepe | 2.08 _(0.03) | 2739 ₍₅₇₈₎ 743 ₍₇₄₃₎ | 0.7 · 10 ³ | 0.82 · 10 ⁵ | 601 | 275 | 1.99 _(0.03) | 0.4 _(0.3) · 10 ³³ | 0.4 · 10 ³³ | 0.36 · 10 ³⁵ | 601 | 302 |
| 3500-3750 | Hyades | 2.09 _(0.03) | 2130 ₍₄₂₆₎ 542 ₍₅₄₂₎ | 1.37 · 10 ² | 0.36 · 10 ⁴ | 174 | 83 | 1.98 _(0.03) | 0.5 _(0.4) · 10 ³³ | 2.04 · 10 ³² | 0.97 · 10 ³⁴ | 174 | 90 |
| | Pleiades | 2.08 _(0.03) | 3487 ₍₇₇₁₎ 171 ₍₁₇₁₎ | 2.19 · 10 ² | 1.62 · 10 ⁴ | 590 | 310 | 2.00 _(0.03) | 3.2 _(2.7) · 10 ³³ | 2.95 · 10 ³² | 1.61 · 10 ³⁴ | 590 | 327 |
| 3750-4000 | Praesepe | 2.02 _(0.03) | 1153 ₍₁₇₃₎ 211 ₍₂₁₁₎ | 1.59 · 10 ² | 1.03 · 10 ⁴ | 970 | 612 | 1.97 _(0.02) | 1.7 _(1.4) · 10 ³² | 2.28 · 10 ³² | 1.42 · 10 ³⁴ | 970 | 663 |
| | Rup 147 | 2.10 _(0.03) | 3226 ₍₁₉₃₎ 132 ₍₁₃₂₎ | 0.67 · 10 ² | 2.81 · 10 ² | 4 | 4 | 1.99 _(0.03) | 0.9 _(0.8) · 10 ³² | 0.9 · 10 ³² | 0.38 · 10 ³³ | 4 | 4 |
| 4000-5000 | Hyades | 2.10 _(0.03) | 1340 ₍₄₀₀₎ 315 ₍₃₁₅₎ | 0.93 · 10 ² | 2.88 · 10 ³ | 52 | 28 | 1.99 _(0.03) | 1.8 _(1.6) · 10 ³³ | 0.72 · 10 ³³ | 1.14 · 10 ³⁴ | 52 | 20 |
| | Pleiades | 2.10 _(0.03) | 1800 ₍₄₄₀₎ 357 ₍₃₅₇₎ | 1.06 · 10 ² | 0.57 · 10 ⁴ | 113 | 69 | 1.99 _(0.03) | 1.5 _(1.3) · 10 ³³ | 0.43 · 10 ³³ | 0.35 · 10 ³⁵ | 113 | 75 |
| 5000-6000 | Praesepe | 2.08 _(0.03) | 180 ₍₃₈₎ 32 ₍₃₂₎ | 0.46 · 10 ² | 1.63 · 10 ³ | 111 | 74 | 1.98 _(0.03) | 1.1 _(0.9) · 10 ³² | 2.19 · 10 ³² | 0.74 · 10 ³⁴ | 111 | 76 |
| | Pleiades | 2.11 _(0.03) | 1346 ₍₃₈₀₎ 300 ₍₃₀₀₎ | 0.98 · 10 ² | 2.05 · 10 ³ | 75 | 35 | 1.99 _(0.03) | 0.6 _(0.5) · 10 ³⁴ | 1.25 · 10 ³³ | 3.03 · 10 ³⁴ | 75 | 36 |
| 567 | Praesepe | 2.10 _(0.03) | 64 ₍₂₆₎ 19 ₍₁₉₎ | 0.56 · 10 ² | 0.37 · 10 ³ | 26 | 10 | 1.99 _(0.03) | 2.7 _(2.4) · 10 ³² | 0.51 · 10 ³³ | 2.95 · 10 ³³ | 26 | 16 |
| | Hyades | 2.10 _(0.03) | 21 ₍₆₎ 9 ₍₉₎ | 1.22 · 10 ¹ | 1.1 · 10 ² | 13 | 7 | 1.98 _(0.03) | 1.5 _(1.3) · 10 ³² | 0.48 · 10 ³³ | 0.53 · 10 ³⁴ | 13 | 6 |
| M67 | Pleiades | 2.09 _(0.03) | 935 ₍₂₄₆₎ 197 ₍₁₉₇₎ | 1.17 · 10 ² | 0.46 · 10 ⁴ | 131 | 55 | 1.98 _(0.03) | 0.3 _(0.3) · 10 ³⁴ | 3.06 · 10 ³³ | 3.01 · 10 ³⁵ | 131 | 59 |
| | Praesepe | 2.08 _(0.03) | 17 ₍₃₎ 12 ₍₁₂₎ | 0.99 · 10 ¹ | 1.52 · 10 ³ | 56 | 47 | 1.98 _(0.03) | 1.2 _(1.0) · 10 ³² | 0.52 · 10 ³³ | 1.03 · 10 ³⁵ | 56 | 37 |
| Rup 147 | M67 | 2.10 _(0.03) | 3 ₍₃₎ 2 ₍₂₎ | 0.6 · 10 ² | 0.6 · 10 ² | 1 | 1 | 1.99 _(0.03) | 0.7 _(0.7) · 10 ³² | 0.62 · 10 ³⁴ | 0.62 · 10 ³⁴ | 1 | 1 |
| | Pleiades | 2.09 _(0.03) | 71 ₍₂₁₎ 17 ₍₁₇₎ | 0.34 · 10 ² | 0.6 · 10 ³ | 35 | 19 | 1.98 _(0.03) | 1.8 _(1.6) · 10 ³³ | 0.5 · 10 ³⁴ | 0.6 · 10 ³⁵ | 35 | 19 |
| Rup 147 | Praesepe | 2.10 _(0.03) | 21 ₍₄₎ 3 ₍₃₎ | 1.49 · 10 ¹ | 1.85 · 10 ² | 76 | 42 | 1.98 _(0.03) | 0.4 _(0.4) · 10 ³³ | 1.68 · 10 ³³ | 0.33 · 10 ³⁵ | 76 | 44 |
| | Rup 147 | 2.10 _(0.03) | 65 ₍₃₈₎ 26 ₍₂₆₎ | 0.56 · 10 ² | 2.16 · 10 ² | 5 | 4 | 1.99 _(0.03) | 1.3 _(1.2) · 10 ³³ | 0.61 · 10 ³⁴ | 2.36 · 10 ³⁴ | 5 | 4 |

Notes. Uncertainties are given in parentheses. Indices _s and _{erg} refer to the units of ED and E_{Kp} FFDs. $E_{\text{Kp},\min}/ED_{\min}$ and $E_{\text{Kp},\max}/ED_{\max}$ are minimum and maximum detected flare ED/energy , n_{tot} is the total number of flares in the sample. n_{fit} is the number of flares used for the power law fit.

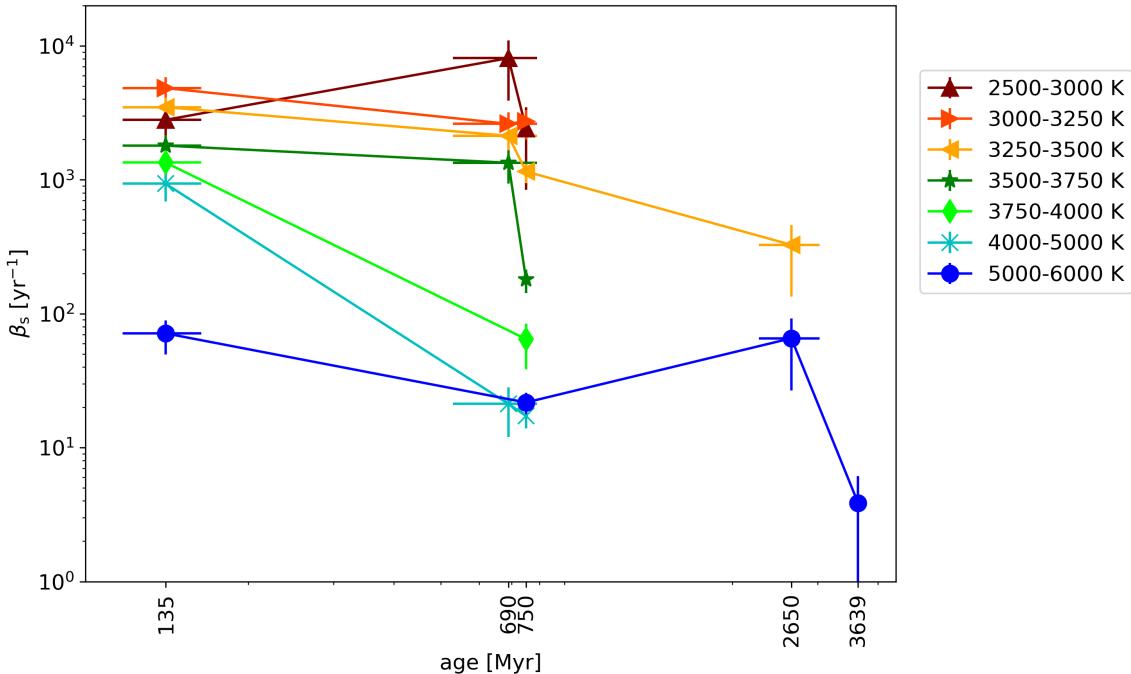


Fig. 8. β_s plotted against age grouped by T_{eff} (different colors and symbols in the legend) in log-log representation. β_s indicates the occurrence rate of flares with $ED = 1$ s (see Eq. 3). It is controlled for stellar luminosity, so that we can compare flaring activity across both age, and T_{eff} , at the same time. The age labels correspond to the OC ages in Table 1.

Table 4. FFD and power law fit parameters to the full flare sample in E_{Kp} and ED (Fig. 5).

| | ED | E_{Kp} |
|--------------------------|---|--|
| α | $2.10 \begin{pmatrix} 0.04 \\ 0.04 \end{pmatrix}$ | $1.98 \begin{pmatrix} 0.03 \\ 0.03 \end{pmatrix}$ |
| $\beta [\text{yr}^{-1}]$ | $2023 \begin{pmatrix} 600 \\ 460 \end{pmatrix}$ | $4.01 \begin{pmatrix} 32.15 \\ 3.55 \end{pmatrix} \cdot 10^{32}$ |
| n_{tot} | 3844 | 3844 |
| n_{fit} | 961 | 1213 |
| min. | 629 s | $6.63 \cdot 10^{32}$ erg |
| max. | 82185 s | $3.01 \cdot 10^{35}$ erg |

Notes. Uncertainties are given in parentheses. min. and max. are minimum and maximum detected flare ED /energy, n_{tot} is the total number of flares in the sample. n_{fit} is the number of flares used for the power law fit.

3500 – 3750 K temperature bin, where the Hyades appeared almost as active as the Pleiades (135 Myr). This discrepancy could be explained by the rotation period distributions of their samples. In all other temperature bins the rotation period distributions of the Hyades and Praesepe were similar, while the Pleiades showed shorter periods on average. In the 3500–3750 K temperature bin, the rotation periods found in the Hyades and the Pleiades were more alike than in the Hyades and Praesepe (see Fig. F.1 in the Appendix). In this temperature regime, the majority of Praesepe stars had rotation periods above 10 d, while in the Hyades and the Pleiades rotation periods were more evenly distributed in the 0.3 – 30 d range.

4.5. M67 and Rup 147: Hypothetic binaries

We found several flare candidates in members of M67 and Rup 147. Upon close inspection all but the events that occurred on four stars either turned out to be false positives, or occurred

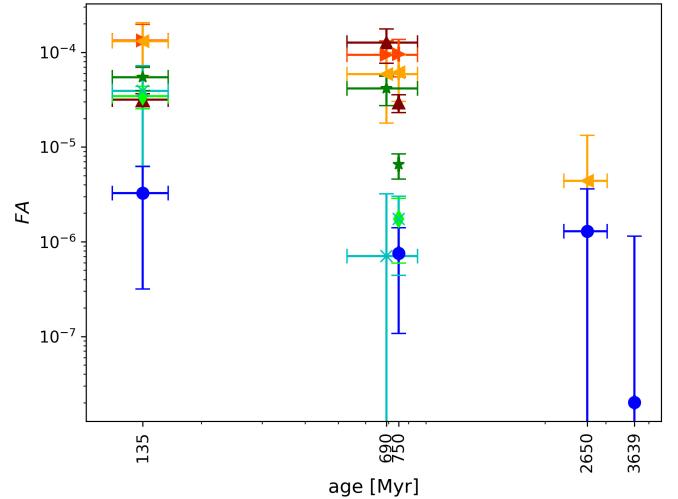


Fig. 9. Median FA and standard deviation plotted against age grouped by T_{eff} in log-log representation. The colors and shapes are the same as in Fig. 8. We used the shared energy threshold ($3.31 \cdot 10^{32}$ erg) that we determined for the full FFD in E_{Kp} in Fig. 5 to calculate FA using Eq. 8. FA is a meaningful measure of relative stellar activity as long as the flux portion of the quiescent star in the Kepler band is roughly constant. It is therefore more meaningful to compare FA across age than across T_{eff} .

on multiple systems or evolved stars. Most flare candidates in these old clusters were detected on RS CVn binaries, cataclysmic binaries, Algol type binaries, spectroscopic and eclipsing binaries, and red giant stars. Excluding all these, we were left with one flare in M67 on an early K dwarf (Fig. 10). In Rup 147, we narrowed down the list to a flare on a G8 star in Rup 147, and four flares each on a K0.5 and an M3 star. For

Table 5. Hypothetic binary configurations for flaring old stars.

| cluster | EPIC | median SpT | binary |
|---------|-----------|------------|-------------|
| M67 | 211434440 | K1 | K2 + M5.5 |
| Rup 147 | 219601739 | G8 | K1 + M6 |
| Rup 147 | 219610232 | K0.5 | K2 + M5.5 |
| Rup 147 | 219591752 | M3 | M3.5 + M3.5 |

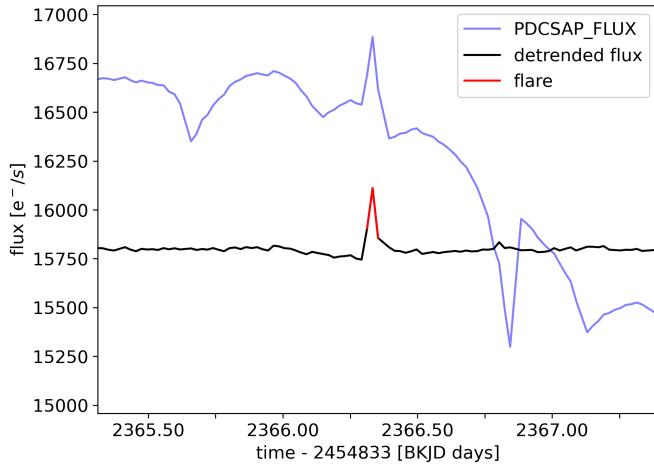


Fig. 10. Single confirmed flare candidate in M67 on the K1 dwarf EPIC 211434440. The amplitude is 2 %, and the flare energy emitted in the Kepler band is $E_{Kp} = 6.25 \times 10^{33}$ erg .

these stars, the multiplicity status was unknown. The uncertainty about the stellar properties suggests a range of possible masses of the system. **The mass budget could be calculated from the uncertainties on their radii R_* using the relations from Eker et al. (2018).** In all cases, it was large enough that the stars in question could in principle be binary stars with undetected mid-M dwarf companions. We calculated hypothetic binary pairs for the cases where the primary mass was the smallest possible within 1σ on R_* . We give the median spectral type of the target if it was a single star, and the spectral types of the hypothetic binaries in Table 5.

After the manual inspection of the younger clusters we concluded that, while binaries and false positives were present in these clusters also, they were not the dominating source of flares. As multiplicity rates for low-mass stars decrease from about 50% for F type stars (Raghavan et al. 2010) to 22% for L and T dwarfs (Duchêne & Kraus 2013), with M dwarfs showing somewhat higher multiplicity rates at about 27% (Winters et al. 2019), we expect that the error introduced by unresolved binaries on our results was smaller for the cooler T_{eff} bins.

5. Discussion

The launch of the Kepler satellite in 2009 caused a surge in statistical flare studies, a trend that the Transiting Exoplanet Survey Satellite will continue and expand. Comparing our results with these works (Shibayama et al. 2013; Lurie et al. 2015; Lin et al. 2019; Raetz et al. 2020) and recent ground based surveys (Chang et al. 2015; Howard et al. 2019) we found encouraging consistency but also some noteworthy discrepancies that we could not always trace back to its cause. We discuss the disagreement between our FFDs and a gyrochronological model recently proposed for its parametrization as a function of mass and age (Davenport

et al. 2019). We conclude the discussion with a reflection on the universality of the power law exponent α , and the observational limitations of the representation of FFDs by power law distributions.

5.1. Consistency with statistical flares studies

We found our results to be broadly consistent with previous work both on Kepler/K2 data, and ground based surveys in the optical regime, with some notable exceptions (Fig. 11). Overall we believe that the differences between individual results were rooted in a combination of astrophysical properties like age, mass, rotation speed, and the influence of selection criteria on the respective samples.

The flare frequency distributions of two fast rotating (0.26 and 0.71 days) M5 flare stars in a M5-M5-M8 triple system (Lurie et al. 2015) were consistent with the FFDs of flares in the Pleiades, Praesepe, and Hyades in the 3000 – 3250 K bin. We also found that the FFDs of nearby K and M dwarfs, observed by Kepler/K2 within 200pc and 100pc, respectively, fell in the range between the Pleiades and Hyades/Praesepe FFDs in our sample (Lin et al. 2019).

The frequency of superflares at 10^{34} erg in the most active G-dwarfs and Sun-like stars in Kepler was once in 10–100 days, and every 440 years on average solar-type stars (Shibayama et al. 2013). Benchmarking on the flare detected on a K1 dwarf in M67 in the G to early K bin (5000–6000 K), and accounting for the fraction of the total flare energy that the Kepler passband covers at a flare temperature of 10 000 K, we found the flaring rate at this energy to amount to about once every 100 years. Doing the same for the Pleiades stars yielded that ZAMS G to K dwarfs flare once per year at 10^{34} erg. Our young G-K stars therefore were less active than the active G dwarfs in Shibayama et al. (2013), while our solar-age G-K dwarfs appeared more active than in their results. Howard et al. (2019) monitored superflares on cool stars with bolometric energies above 10^{33} erg and up to 10^{36} erg. They found power law exponents ~ 2 in FFDs resolved by spectral type. The activity levels for spectral types K5 to M4 were on average higher than in our sample. However, Howard et al. (2019) only included stars that exhibited flares (active stars) into their FFDs, whereas we also accounted for the observing time of stars where no flares had been detected.

Photometric flares observed by the MMT 6.5 telescope (Hartman et al. 2008) in the ~ 550 Myr old open cluster M37 (Chang et al. 2015) appeared on average more active than the Pleiades in our study for spectral types M0–M6. This could imply that flaring activity in these low-mass stars peaked not at Pleiades age but at a later evolutionary stage. Mondrik et al. (2019) found evidence of increased flaring activity at intermediate rotation rates between fast and slow sequence (Barnes 2003). This finding could not be reproduced in the data obtained from the all-sky EvryFlare survey (Howard et al. 2020). We found β_s to decrease with age from ZAMS to 700 Myr for all stars except those with spectral types later than M5 (Fig. 8). But this does not exclude that β_s in fact increased between these two ages before decreasing relatively rapidly within a short period of time.

Similarly, Raetz et al. (2020) pointed out that their fast rotating M1.5–M4.5 dwarfs appeared more active than the results for the Pleiades in PaperI in the 3250 – 3750 K range. Our revised results remained consistent with PaperI (Fig. 11). For comparison, we used our method to search a star that both studies investigated for flares. In Fig. 12, we demonstrate that short cadence light curves used in Raetz

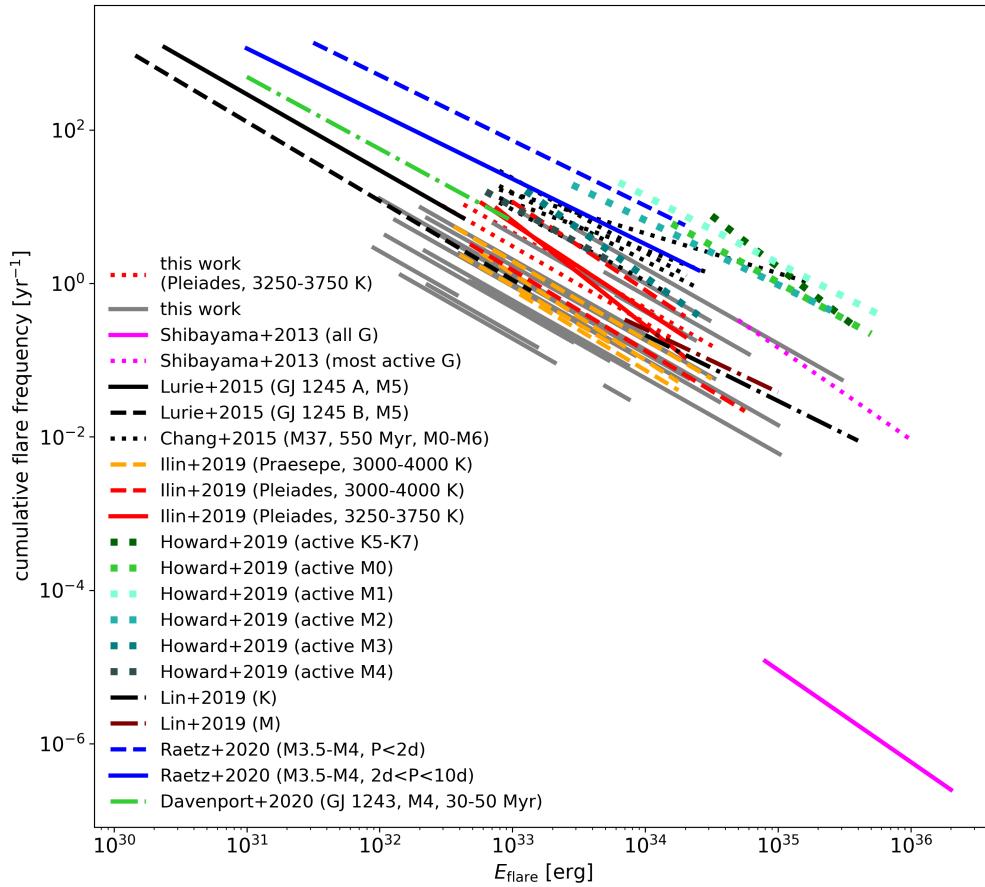


Fig. 11. Comparison of FFDs found in different flare studies. Grey lines: Flare frequency distributions from this work. The one-flare sample for 5000–6000 K in M67 is indicated as the shortest visible grey line. Red solid lines, and red and orange dashes: K2 long cadence light curves study of the Pleiades and Praesep, respectively, in four T_{eff} bins from 3000 to 4000 K each (PaperI). Magenta line and dots: Superflares on all G dwarfs in Kepler, and its most active sub-sample (Shibayama et al. 2013). Black line and dashes: Two M5 stars in an M5-M5-M8 triple system observed by Kepler (Lurie et al. 2015). Black dots: Flare study based on MMT survey of the ~ 550 Myr old open cluster M37 (Chang et al. 2015). Dots in shades of green to blue: Evryscope all-sky flare search on late K to mid M dwarfs (Howard et al. 2019). Black and brown dash-dotted lines: K2 long-cadence study of K and M dwarfs within 200pc and 100pc (Lin et al. 2019). Dark blue line and dashes: K2 short cadence light curves of M3.5–M4 dwarfs with known rotation periods below 2 d and between 2 and 10 d respectively (Raetz et al. 2020). **Green dash-dotted line:** The 30 – 50 Myr old M4 flare star GJ 1243 exhibited a constant flaring activity for over a decade of intermittent space based observations with Kepler and TESS (Davenport et al. 2020).

et al. (2020), and long cadence light curves studied here yielded consistent FFDs. Both samples were comprised of flares with periods below 10 d. Rotation periods P_{rot} were given for 100% of the sample in Raetz et al. (2020), and for $> 85\%$ in our Pleiades sub-sample (see Fig. F.1 in the Appendix for the distribution of P_{rot}). We note three plausible reasons for the discrepancy here. First, the M1.5–M4.5 dwarfs in Raetz et al. (2020) could be stars at a an age at which the stars show higher flaring activity than stars with the same rotation periods in the Pleiades. Second, there may be selection effects in the short cadence sample in Raetz et al. (2020) as compared to our sample. Targets for short cadence observations in K2 were not selected randomly from the underlying stellar population, but were filtered for a variety of properties that biased the final selection towards more active stars. Third, our 3250 – 3750 K corresponds rather to spectral types M1–M3.5 than to M1.5–M4.5 (Pecaut & Mamajek 2013). So the T_{eff} bins chosen in Raetz et al. (2020) encompassed later, and therefore more active, spectral types. Eventually, a resolution of this discrepancy must also take into account that the results for our Praesep sample in the

3250 – 3750 K range were consistent with the slow rotators ($P_{\text{rot}} \sim 32$ d) in Raetz et al. (2020).

5.2. Gyrochronological FFD parametrization

Davenport et al. (2019) derived a parametrization of FFD parameters α and β as a function of mass and age using the Kepler flare catalog (Davenport 2016), rotation periods from McQuillan et al. (2014), and the Mamajek & Hillenbrand (2008) gyrochrone model. We show the model power laws in Fig. 7 alongside our results. The activity level in our sample appeared much lower than predicted by the model. A deviation was expected as the model was not designed to predict absolute ages. The authors noted a sample bias in their study towards more active stars. As discussed by the authors, their model overpredicted the superflaring rate of the average Sun-like sample from Shibayama et al. (2013) and more resembled the rate for their most active sub-sample. With our data we could quantify the overestimation to be one to two orders of magnitude. Our results also suggest

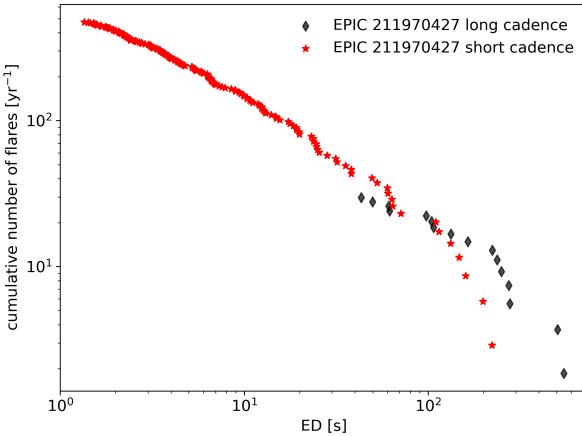


Fig. 12. FFDs in ED for EPIC 211970427, an M3 dwarf in Praesepe that was observed in both short cadence (campaigns 5, 18) and long cadence (campaigns 5, 16, and 18). We detrended, and searched both light curve types for flares using the method described in Sec. 3.1. Red stars indicate flares found in the short cadence light curves, grey diamonds are flares from the long cadence time series. There are no exactly matching events in the FFD although a subset of the short cadence flares was detected in long cadence also. This has two reasons. First, in long cadence, flare energy is typically underestimated (Yang et al. 2018). Second, smaller flares are merged together if they occur within a sufficiently short time period. What looks like one flare in long cadence is sometimes resolved into two or more flares in short cadence.

that the model overpredicts the activity level for old stars more than for younger stars (Fig. 7).

5.3. Universality of α

Taking into account uncertainties and systematic errors resulting from the use of different power law fitting methods (Maschberger & Kroupa 2009), the power law exponent $\alpha \sim 2$ appeared to be similar for the majority of studies on flare statistics in the literature so far, irrespective of spectral type or age. The values derived for α in our sample were close to 2 in ED space, and ~ 2.1 in E_{Kp} , consistent with previous work (Fig. G.1 in the Appendix). The determination of α usually faces methodological challenges that make it difficult to assess whether the spread in α from about 1.4 to 2.5 is physically motivated or not.

For both low and high energies, the detection of flares was incomplete. At the low-energy end the detection probability depended on flare duration and amplitude. These parameters were not resolved in FFDs, and while they were correlated there is significant spread in the duration-amplitude relation to blur the cutoff in the FFD. One way to account for this circumstance is to inject and recover large numbers of synthetic flares with a variety of durations and amplitudes and to determine energy ratios and recovery probabilities for each flare candidate, assuming that the underlying flare shape can be sufficiently well parametrized. This was first explored in Davenport et al. (2014) for Kepler data and expanded in (Schmidt et al., in prep.) for TESS. However, GP regression, which was used to de-trend the light curves, was too costly to be repeated hundreds of times for each light curve. At the high energy end, the incompleteness is most likely to occur in the full sample FFDs where we expect either

observational or physical maximum energy thresholds to be reached for certain spectral types and ages.

These effects may be partly cancelled by background contamination from, for instance, cosmic rays (Aschwanden 2015), or solar system objects (SSO). We were also limited by the non-linear dependence for the energy bias from time sampling effects that lead to the severe underestimation of flares energies, as can be observed by comparing flare energies derived for the same flare events from short and long cadence light curves (Yang et al. 2018). As long as these caveats apply, the question about the universal nature of α cannot be settled.

5.4. Deviations from single power law

Spots can survive on the stellar surface from a few days to nearly a year (Namekata et al. 2017; Davenport 2015). Complex spot geometry is correlated with the strongest X-class flares on the Sun (Toriumi et al. 2017; Sammis et al. 2000). These observations support the idea that flares are associated with the presence of certain types of starspots, or more generally, certain types of active regions. Since we expect that there is a maximum flare energy a spot can produce, the underlying power law relation must break a some ED_{\max} in any FFD. We tested a possible truncation of our FFDs using the Kolmogorov-Smirnov test for consistency with a power law distribution, followed by the exceedance statistic to test for a truncation of this power law as suggested by Maschberger & Kroupa (2009). While most FFDs with ≥ 50 flares were consistent with a power law distribution, we found no evidence for truncation in any of the T_{eff} -age bins. This would imply that we did not sample the highest possible energies. Such a conclusion is plausible because much higher relative fluxes than our observed maximum flare amplitudes were detected on other stars (Paudel et al. 2018; Jackman et al. 2019; Schmidt et al. 2016).

6. Summary and Conclusions

In this study, we investigated how flaring activity unfolded for different age and T_{eff} ranges anchoring the age to the membership in five open clusters. We found flaring activity to decrease from ZAMS to solar age, and from mid M dwarfs to G stars, except for stars later than M5, where activity increased from ZAMS to 690 Myr.

Using multiple cluster membership studies we selected for high-probability members, and drew from a host of multiband photometry catalogs to determine T_{eff} and stellar luminosities. Keeping only targets with well-determined mass and age we proceeded to search 3435 K2 long cadence light curves obtained for these stars throughout the K2 mission. We applied the open source software K2SC to remove rotational variability and instrumental effects, and AltaiPony to automatically detect and determine the properties of flare candidates. We vetted all flare candidates manually and discussed various sources of false positives and incompleteness on both the high and the low energy end of the FFDs. We searched 2111 stars in five open clusters, and found a total of 3844 flares. Most flares originated in the Pleiades and Praesepe, several hundred were found in the Hyades, a handful in Rup 147, and only one flare candidate appeared on a K1 dwarf in M67.

While the FFDs appeared to follow power law distributions, we found no sign of truncation at the high energy end. The power law exponent α was consistent with previous work, and we caution against interpreting apparent trends, especially when comparing across different studies.

We noticed that our results showed lower activity than predicted by a gyrochronological FFD parametrization as a function of mass and age (Davenport et al. 2019), and that the model did not always match the differential decline in age within individual T_{eff} bins. Although some discrepancies in flaring activity between Praesepe and the Hyades could be traced back to their rotation period distributions, the relation between flaring, rotation, and age awaits further investigation.

Regardless of varying methods employed for flare search and FFD analysis in previous studies we found encouraging consistency in flaring rates with both Kepler and K2 based work, and ground-based surveys. We noticed some differences, which we could not always resolve as being either systematic or astrophysical. We suggest that discrepancies between our results and flare studies that used rotation periods for their age estimates (Davenport et al. 2019; Raetz et al. 2020) could be explained by sample selection bias but may also point to limitations of rotation periods as an age indicator.

Results from the first year of operations of the Transiting Exoplanet Survey Satellite (Ricker et al. 2014) indicate that the light curve quality delivered by the mission so far was well suited for statistical flare studies (Doyle et al. 2020; Günther et al. 2020). The expected lifetime of the mission could be up to 20 years, in which case the number of high quality flare samples will soon outclass Kepler and K2 as the primary source of flares. Not only will the mission vastly expand the treasury of light curves, help us address open questions noted in this work and other statistical flares studies, and pave the road to the use of flaring activity as an age indicator. It will also allow us to probe the flaring activity of the lowest mass dwarfs down into the brown dwarf regime, a realm that could only be scratched by Kepler and K2 (Gizis 2013; Paudel et al. 2018), and remains mostly inaccessible from the ground.

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Appendix A: Membership probabilities

To match catalogs on RA and declination we used the `astroML.crossmatch` tool for Python (Vanderplas et al. 2012). For the studies with classifiers we assigned membership probabilities as follows. In Gonzalez (2016):

$$\begin{aligned} p(M(\text{member})) &= 0.9, \\ p(BM(\text{binary member})) &= 0.9, \\ p(N(\text{non-member})) &= 0.1, \\ p(SN(\text{single non-member})) &= 0.1, \\ p(BN(\text{binary non-member})) &= 0.1, \\ p(U(\text{unknown member})) &= 0.5. \end{aligned}$$

In Curtis et al. (2013):

$$\begin{aligned} p(Y(\text{highest confidence member})) &= 0.9, \\ p(P(\text{possible/probable member})) &= 0.7, \\ p(N(\text{not likely/non-member})) &= 0.7, \\ p(B(\text{photometry consistent with blue stragglers})) &= 0.0. \end{aligned}$$

In Rebull et al. (2017):

$$\begin{aligned} p((\text{best})) &= 0.9, \\ p((\text{ok})) &= 0.6, \\ p((\text{else})) &= 0.1. \end{aligned}$$

Members from Rebull et al. (2016); Douglas et al. (2017); and Gaia Collaboration et al. (2018a) were assigned $p = 0.9$ if they appeared in the final catalog.

Table A.1 gives an overview over different membership catalogs. Figure A.1 shows membership probability histograms of the final sample broken down by membership source.

Appendix B: Cluster parameters

We compiled various age, distance, and metallicity values from the literature for the clusters in this study. Table B.1 shows that most studies independently arrived at similar results for all our clusters. The adopted parameters are emphasized, and were chosen based on consistency with prior work, uncertainties provided with the results and the data used for the study (newer catalogs were preferred).

Appendix C: Broadband photometry: quality cuts and conversions

We required `flux/flux_error` ≥ 10 for Gaia *G*, *BP*, and *RP* bands. We require that the 2MASS measurements for *J*, *H*, and *K* to be "A". "A" meant that measurements had $S/N > 10$ and $\sigma < 0.11$. For PanSTARRS photometry, we required that the `QF_OBJ_GOOD` quality filter flag was set. SDSS and PS1 *ugrizy* bands were similar but not identical, but could be converted using Table 2 in Finkbeiner et al. (2016).

Appendix D: Solar System Object detection with SkyBot

The K2 photometry was heavily affected by crossings of Solar System Objects (SSO), which consequently produced mimicking flare profiles in the light curves (Szabó

et al. 2015). Independently, two of us visually verified the SSO-nature of 42 flaring light curve events by inspecting their corresponding TargetPixelFiles (TPF) using `lightkurve` (Lightkurve Collaboration et al. 2018). Except for one occasion, we found all events to be known SSOs, both in the visual survey and automatically using SkyBot (Berthier et al. 2016). Subsequently, we ran SkyBot on the remaining catalog of flares to remove other false positive events caused by known SSOs. Visual inspections of TPFs were carried out for any SSO detected within $30''$ of its target star at mid-event time. This yielded additional 103 contaminated signals distributed among three subgroups, (i) 77 unambiguous SSO-contaminants verified through `lightkurve` (ii) 18 faint SkyBot-detections ($V \approx 20.4 - 23.8$) within ~ 3 pixels from the respective target star but visually unresolvable in the TPF, (iii) 8 occurrences in which both flare and SSO-crossing occurred during the given flare duration stated in the catalog. The latter should be dealt with caution due to a high risk of inaccurate catalog information altered by the presence of SSOs. Despite of discarding a total of 144 flare events, we expect additional contaminants by unknown SSOs to hide in the current sample. This issue can partly be resolved by animating each TPF as demonstrated by Kristiansen et al. (in prep.).

Appendix E: Modified Maximum Likelihood Estimator

As a means to arrive at results efficiently, and as consistency check to the method derived from Wheatland (2004) we fitted α to the FFDs in *ED* and E_{Kp} space using a Modified Maximum Likelihood Estimator (MMLE, Maschberger & Kroupa 2009). The logarithm of the likelihood function \mathcal{L} that had to be maximized was given by the authors in Eq. (8) in their manuscript:

$$\log \mathcal{L} = n \log(1 - \hat{\alpha}) - n \log(x_{\max}^{1-\hat{\alpha}} - x_{\min}^{1-\hat{\alpha}}) - \hat{\alpha} \sum_{i=1}^n \log x_i \quad (\text{E.1})$$

where x_i , x_{\max} , and x_{\min} were the detected flare energies, and the upper and lower limits for detection, respectively. n was the total number of flares. The estimate for α would be biased in practice because the value used for x_{\max} would be the maximum energy that was measured, and not the underlying upper limit. The stabilization transformation suggested by the authors (Eq. (12) in Maschberger & Kroupa 2009) was then applied to the solution for α to account for this bias:

$$\alpha = 1 + \frac{n}{n-2}(\hat{\alpha} - 1) \quad (\text{E.2})$$

Using the MMLE method on the full sample of flares in E_{Kp} and *ED* space we obtained $\alpha_{\text{erg}} = 1.97$ and $\alpha_s = 2.06$, respectively, indicating a marginally flatter power law than the predictive model ($\alpha_{\text{erg}} = 1.98$, $\alpha_s = 2.1$).

Appendix F: Rotation and flaring

More energetic flares can be expected from faster rotating stars (Candelaresi et al. 2014; Doorslaere et al. 2017; Yang et al. 2017). However, the famous $\text{age}^{-1/2}$ Skumanich spin-down law for rotation braking and Ca II depletion as a proxy to magnetic activity (Skumanich 1972) was only ever true to a first approximation. One example of non-linear spin-down was

Table A.1. Membership catalogs used in this work.

| source | type | clusters covered | notes |
|-----------------------------------|--------------|---|-----------------|
| Curtis et al. (2013) | classifier | Rup 147 | |
| Douglas et al. (2014) | probability | Hyades, Praesepe | meta study |
| Gonzalez (2016) | classifier | M67 | |
| Rebull et al. (2016) | members list | Pleiades | meta study |
| Rebull et al. (2017) | classifier | Praesepe | meta study |
| Douglas et al. (2017) | members list | Praesepe | meta study |
| Gaia Collaboration et al. (2018a) | members list | Hyades, Rup 147, Pleiades, Praesepe | Gaia DR2, (1) |
| Cantat-Gaudin et al. (2018) | probability | Rup 147, Pleiades, Praesepe | Gaia DR2 |
| Gao (2018) | probability | M67 | Gaia DR2 |
| Reino et al. (2018) | probability | Hyades | Gaia DR1, (1) |
| Olivares et al. (2018) | probability | Pleiades | Gaia DR2, DANCe |
| Olivares et al. (2019) | probability | Rup 147 | Gaia DR2, DANCe |

Notes. **Meta study:** See references in the studies for additional membership information. **DANCe:** DANCe membership study project. **Gaia DR1:** The study used data from the first data release (Gaia Collaboration et al. 2016a) of the Gaia mission (Gaia Collaboration et al. 2016b). **Gaia DR2:** The study used data from the second data release (Gaia Collaboration et al. 2018b). (1): Positions for Hyades were propagated to epoch 2000 using Gaia proper motions.

the apparent temporary stalling of spin-down seen in K dwarfs in the 1 Gyr old open cluster NGC 6811 (Curtis et al. 2019). As our results indicate, the decline of flaring activity with age did not follow the Skumanich law across the stellar main sequence life time. Moreover, it depended crucially on T_{eff} (see Fig. 8). In Fig. F.1 we show rotation periods derived from K2 light curves for the Pleiades (Rebull et al. 2016), the Hyades and Praesepe (Douglas et al. 2019), to illustrate the P_{rot} distributions that correspond to our T_{eff} bins.

Appendix G: Universality of α

We searched the literature for studies where power laws were fitted to FFDs of flares in the optical regime using different methods (see Fig. G.1 for a comparison). While most studies consistently find values somewhat above or below $\alpha \approx 2$, the comparison would reveal unresolved systematic errors in all these studies, including our own, if α was truly universal for all FFDs.

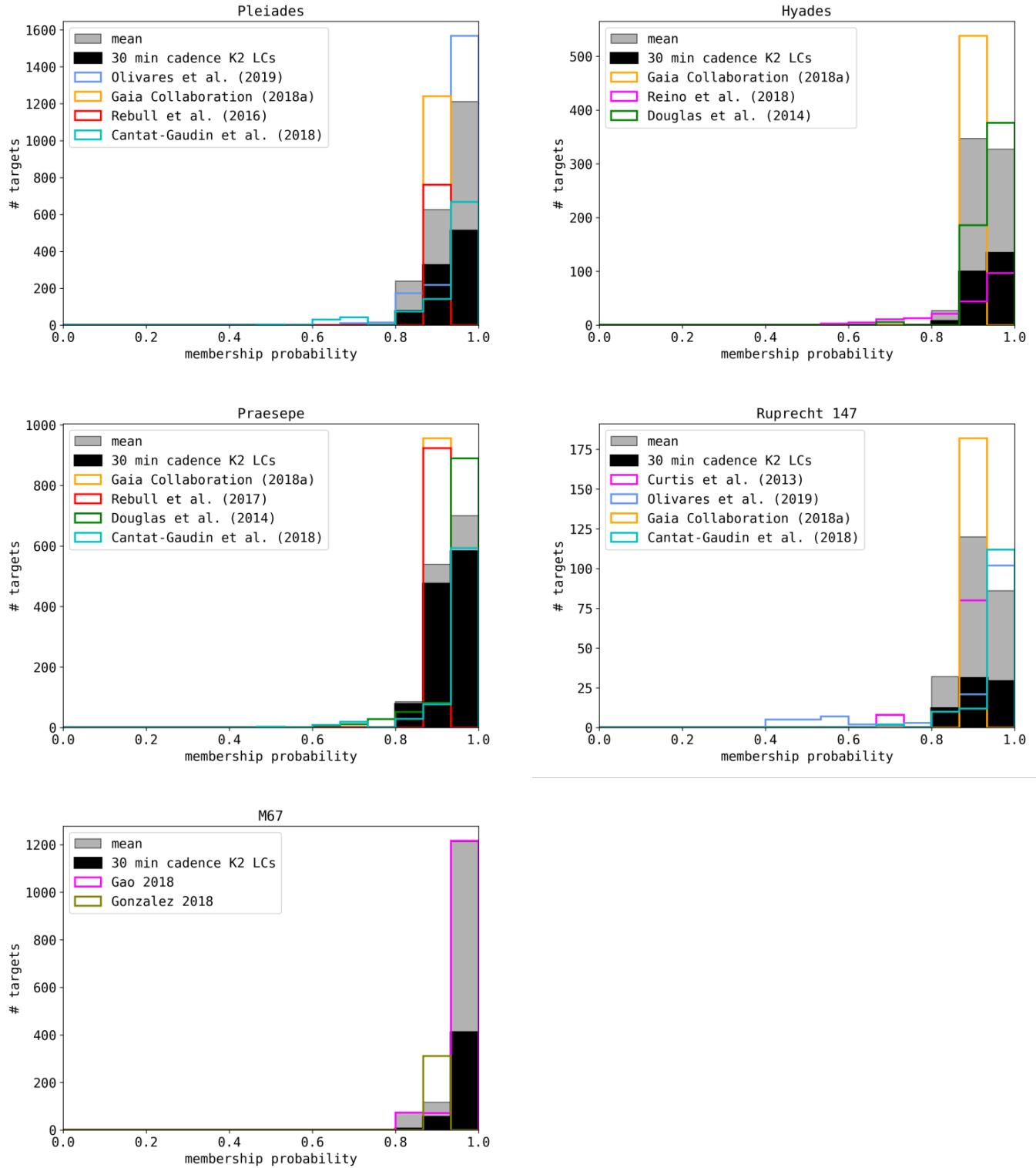


Fig. A.1. OC membership histograms and selected targets. Each panel corresponds to the distribution of candidate members of the cluster indicated in the panel title. Membership catalogs are shown as step histograms (different colors). The mean membership probability distribution is a filled histogram (grey). For our study, we selected only stars with membership probabilities above 80% that were observed by K2 in long cadence mode (black filled histogram).

Table B.1. Non-exhaustive literature overview over OC parameters.

| cluster | source | distance [pc] | age [Myr] | [Fe/H] |
|-----------------|---|---------------|-----------------|--------------------|
| Pleiades | adopted in this work: | 135.6 | 135 ± 25 | -0.037 ± 0.026 |
| | Bossini et al. (2019) ^a | | 86.5 ± 6 | |
| | Cantat-Gaudin et al. (2018) | 135.6 | | |
| | Gossage et al. (2018) | | 135 ± 25 | |
| | Yen et al. (2018) | 126.3 | 141.3 ± 170 | |
| | Chelli & Duvert (2016) | 139 | | |
| | Netopil et al. (2016) | | | -0.01 |
| | Dahm (2015) | | 112 ± 5 | |
| | Scholz et al. (2015) | 130 | 120 | |
| | Conrad et al. (2014) | | | -0.037 ± 0.026 |
| | Melis et al. (2014) | 136 | | |
| | Bell et al. (2012) | 135 | 125 | |
| Hyades | adopted in this work: ^c | | 690 ± 160 | 0.13 ± 0.02 |
| | Gaia Collaboration et al. (2018a) | | 690 ± 100 | |
| | Gossage et al. (2018) | | 680 | |
| | Liu et al. (2016) | | | ± 0.02 |
| | Netopil et al. (2016) | | | 0.13 |
| | Taylor & Joner (2005) | | | 0.103 ± 0.008 |
| | Salaris et al. (2004) | | 650 | 0.15 |
| | Perryman et al. (1998) | | 625 ± 50 | |
| Praesepe | adopted in this work: | 185.5 | 750 ± 3 | 0.16 |
| | Bossini et al. (2019) | | 750 ± 7 | |
| | Cantat-Gaudin et al. (2018) | 185.5 | | |
| | Gossage et al. (2018) | | 590 | |
| | Yen et al. (2018) | 183 | 794 ± 253 | |
| | Netopil et al. (2016) | | | 0.16 |
| | Scholz et al. (2015) | 187 | 832 | |
| | Boesgaard et al. (2013) | | | 0.12 |
| | Boudreault et al. (2012) | 160 | 630 | |
| | Salaris et al. (2004) | 175 | 650 | |
| Rup 147 | adopted in this work: | 305 | 2650 ± 380 | 0.08 ± 0.07 |
| | Bragaglia et al. (2018) | | | 0.08 ± 0.07 |
| | Cantat-Gaudin et al. (2018) | 305 | | |
| | Gaia Collaboration et al. (2018a) | 309 | 1995 ± 404 | |
| | Torres et al. (2018) | 283 | 2650 ± 380 | |
| | Curtis (2016) ^b | | | 0.10 ± 0.02 |
| | Scholz et al. (2015) | 270 | 1953 | |
| | Curtis et al. (2013) | 300 | 3125 ± 125 | 0.07 ± 0.03 |
| M67 | adopted in this work: | 908 | 3639 ± 17 | $-0.102 \pm .081$ |
| | Bossini et al. (2019) | | 3639 ± 17 | |
| | Netopil et al. (2016) | | | 0.03 |
| | Scholz et al. (2015) | | 3428 ± 147 | |
| | Conrad et al. (2014) | | | $-0.102 \pm .081$ |
| | Dias et al. (2012) | 908 | 4300 | |
| | Önehag et al. (2011) | 880 | 4200 | 0.02 |
| | Salaris et al. (2004) | | 4300 ± 500 | 0.02 ± 0.06 |

Notes. ^(a) Bossini et al. (2019) noted some caveats for their determination of ages of young clusters, for which they used Gaia DR2 photometry for isochrone fitting. ^(b) Curtis (2016) reanalysed HIRES spectra using an improved spectroscopic method as compared to Curtis et al. (2013). ^(c) We did not adopt a mean value for the Hyades distance because the cluster members are on average closer than 50 pc.

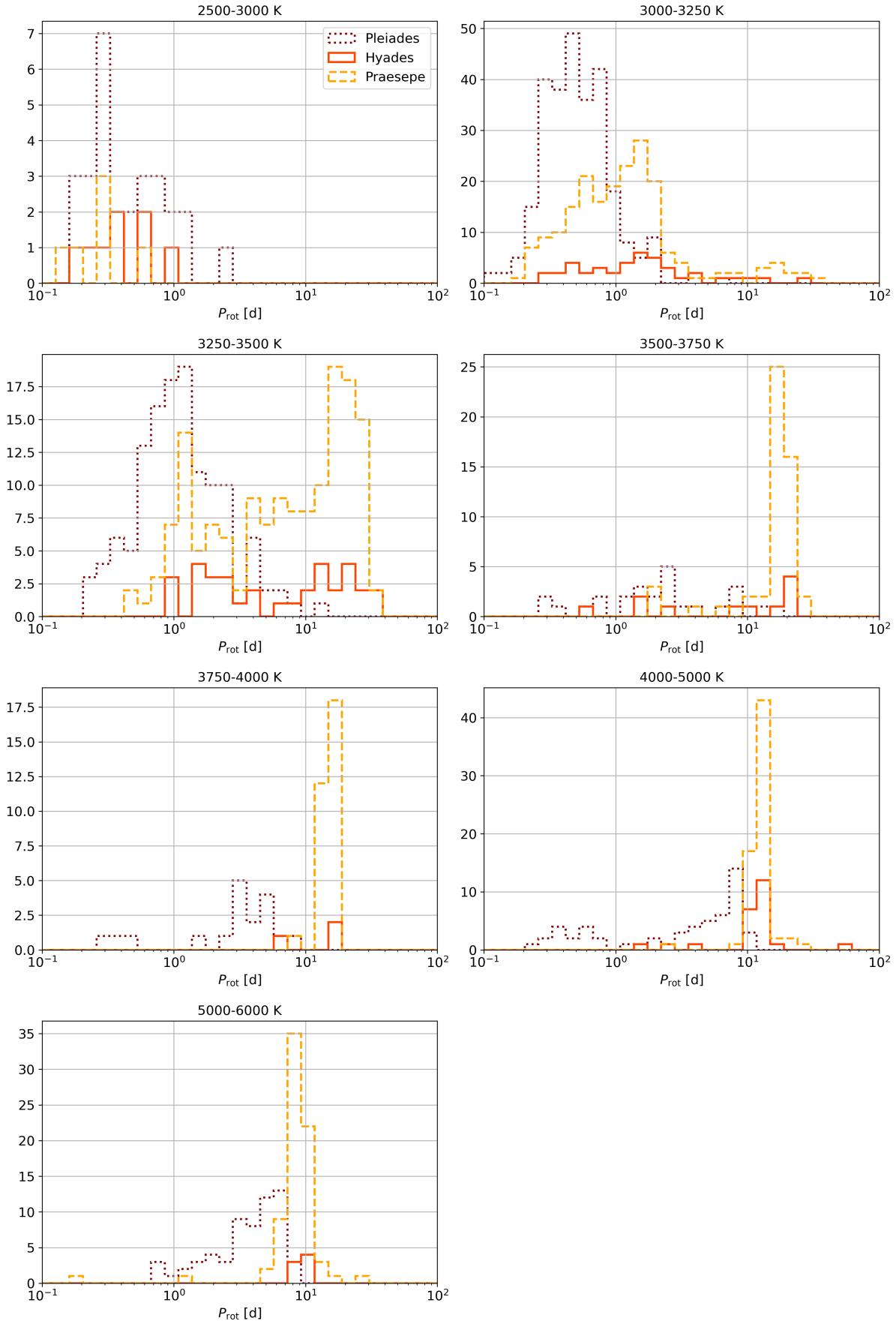


Fig. F.1. Rotation histograms for the cluster members that were searched for flares and had measured rotation periods P_{rot} . Rotation periods were taken from Douglas et al. (2019) for the Hyades (orange solid) and Praesepe (yellow dashed), and from Rebull et al. (2016) for the Pleiades (maroon dotted). Rotation periods were available for 51 – 100% of the stars that we searched for flares with a median of 80%.

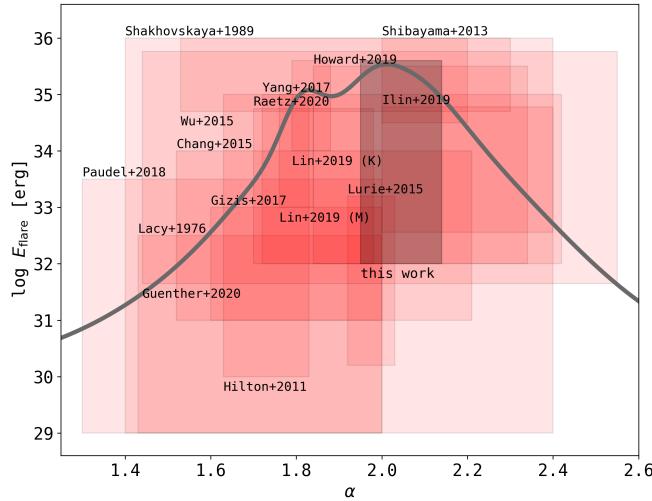


Fig. G.1. Literature overview over power law fits to FFDs. Red rectangles indicate the energy range in which flares were detected (height), and the range of values determined for the power law exponent α (width) including quoted uncertainties and superimposing the ranges for α from multiple FFDs if any. The references are attached to the upper or lower left corner of the respective rectangle. The grey rectangle refers to this study. The grey line depicts the superposition of these results, representing each by a Gaussian fit with the range used as standard deviation, and weighted by the square root of the number of flares found in each study. PaperI is shown with a dark outline. Lacy et al. (1976) pioneered in statistical flare studies using observations of eight UV Ceti stars. Shakhovskaya (1989) analyzed monitoring data from several dozen active early K to late M dwarfs in the solar vicinity, the Orion, the Pleiades, the Hyades, and the Praesepe cluster. Hawley et al. (2014) used flares from M dwarfs in the original Kepler observations for their FFDs. A number of studies focused on solar-type and G dwarfs stars in Kepler (Maehara et al. 2012; Wu et al. 2015; Shibayama et al. 2013). Hilton (2011) derived α from ground-based observations of M dwarfs. Lurie et al. (2015) determined α from Kepler short cadence light curves of two active M5 dwarfs in Kepler. Davenport (2016) searched the entire Kepler catalog for flares. Yang et al. (2017) followed up on Davenport (2016) in searching the entire Kepler catalog for flares. Lin et al. (2019) (M) and (K) were based on nearby M and K dwarf flares in K2 long cadence light curves. (Raetz et al. 2020) studied short cadence M dwarfs with rotation periods in K2. Gizis (2017) constructed an FFD for 22 flares on an M7 dwarf. Paudel et al. (2018) studied M6-L0 dwarfs in K2 short cadence data. Howard et al. (2019) found over 500 superflares on 284 stars in the framework of the Evryscope all-sky survey. Photometric flares were observed by the MMT 6.5 telescope (Hartman et al. 2008) in the ~ 550 Myr old M37 open cluster (Chang et al. 2015). Finally, (Günther et al. 2020) took a first look to α as derived from stars observed during TESS Cycle 1. From their work we only use α derived from stars with 20 or more flare detections.