

# 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 unmistakable 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 2256 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 2918 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 (650 Myr) as a comparison cluster to Praesepe (690 Myr), the 2.5 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  $\alpha \approx 1.8 - 2.0$ . 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). Their high intensity and contrast allow us to measure magnetic activity as traced by flares for a broad range of stars.

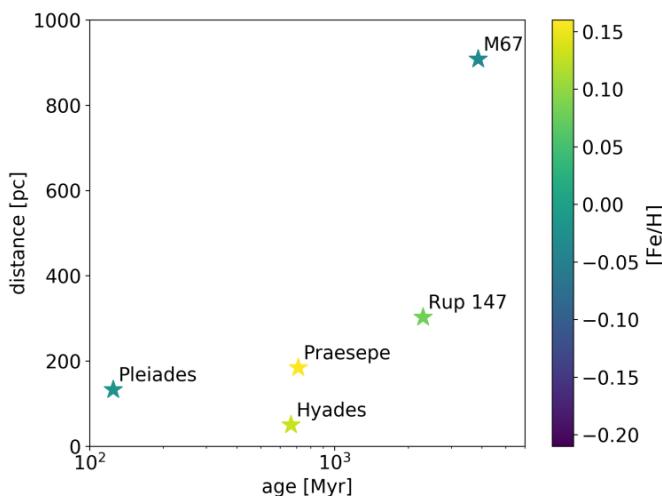
Statistical flare studies have been pioneered from the ground (Lacy et al. 1976). But it was not until space missions like Kepler (Koch et al. 2010) and the Transiting Exoplanet Survey Satellite (Ricker et al. 2014) enabled the investigation of stellar ensembles that were not pre-selected for their activity (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. 2019b), how flares relate to stellar angular momentum evolution (Mondrik et al. 2019; Howard et al. 2019b), 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. 2019a).

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, 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. 2019a). In gyrochronology, fast rotation indicates young age (Barnes 2003), and slows down as the star ages. Chromospheric activity was also explored as an age tracer in the past (Soderblom et al. 1991; Pace 2013; Lorenzo-Oliveira et al. 2016)

While absolute stellar ages are difficult to assess, they can at least be differentially controlled for in coeval groups of



**Fig. 1.** The values for age, metallicity, and distance are approximate values from a compilation of existing literature, see Appendix B.

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 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 open clusters (OCs), the Pleiades, Praesepe, and M67, using K2 time domain photometry. They analyzed flare frequency distributions (FFDs) broken down by the stars' effective temperatures  $T_{\text{eff}}$  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 (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  $T_{\text{eff}}$ , 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 understudied (Barentsen et al. 2018). In this spirit we took up the analysis of a total of 2256 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 pipeline (Aigrain et al. 2016) with minor modifications to de-trend the 36th data release of the K2 data products. It was considered the final data release, and included a uniform, global reprocessing of most K2 campaigns using an improved data reduction pipeline<sup>1</sup>.

### 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. 2016a; 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. Absence in a catalog did not decrease the likelihood of membership, as each catalog shows 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. A literature overview of age, distance, and metallicity determinations is given in Table B.1 in the Appendix. Membership probability histograms of the final sample are displayed in Figure A.1.

#### 2.2.1. Pleiades

The Pleiades, a nearby ZAMS cluster, was observed in Campaign 4, and treated in PaperI. We include the cluster in this work for completeness, and to include methodological improvements to (PaperI). We revisited the members from Rebull et al. (2016a), 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).

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

**Table 1.** Open clusters.

	d [pc]	stars	LCs	flares	campaigns	age [Myr]	[Fe/H]
Pleiades	135.6	741	741	1605	1	135 $\left(\frac{25}{25}\right)$	-0.04(0.03)
Hyades	46.0	170	179	407	2	690 $\left(\frac{100}{160}\right)$	0.13(0.02)
Praesepe	185.5	913	1965	1914	3	750 $\left(\frac{7}{3}\right)$	0.16(0.00)
Rup 147	305.0	53	53	9	1	2650 $\left(\frac{380}{380}\right)$	0.08(0.07)
M67	908.0	234	497	2	3	3639 $\left(\frac{17}{17}\right)$	-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, which is detailed in Appendix B.1. The uncertainties are noted in parentheses. "stars" denotes the approximate number of cluster members with membership probability  $p > 0.8$ . "LCs" and "campaigns" is the number 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.

### 2.2.2. 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).

### 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 memberships obtained by Douglas et al. (2014), and matched them to the members identified in Douglas et al. (2017); Rebull et al. (2017); Cantat-Gaudin et al. (2018); and Gaia Collaboration et al. (2018a).

### 2.2.4. Ruprecht 147

Ruprecht 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 most likely members.

### 2.2.5. M67

M67 is a solar-age, solar metallicity OC about 900 pc away. Multiple members were observed during Campaign 5, and revisited in Campaigns 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. 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  $T_{\text{eff}}$  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. 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 Ruprecht 147 for

extinction using the most recent version (Green et al. 2019) of the dustmaps package that provides 3D dust maps derived from 2MASS and PanSTARRS photometry together with Gaia distances (Green et al. 2018). 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 $T_{\text{eff}}$

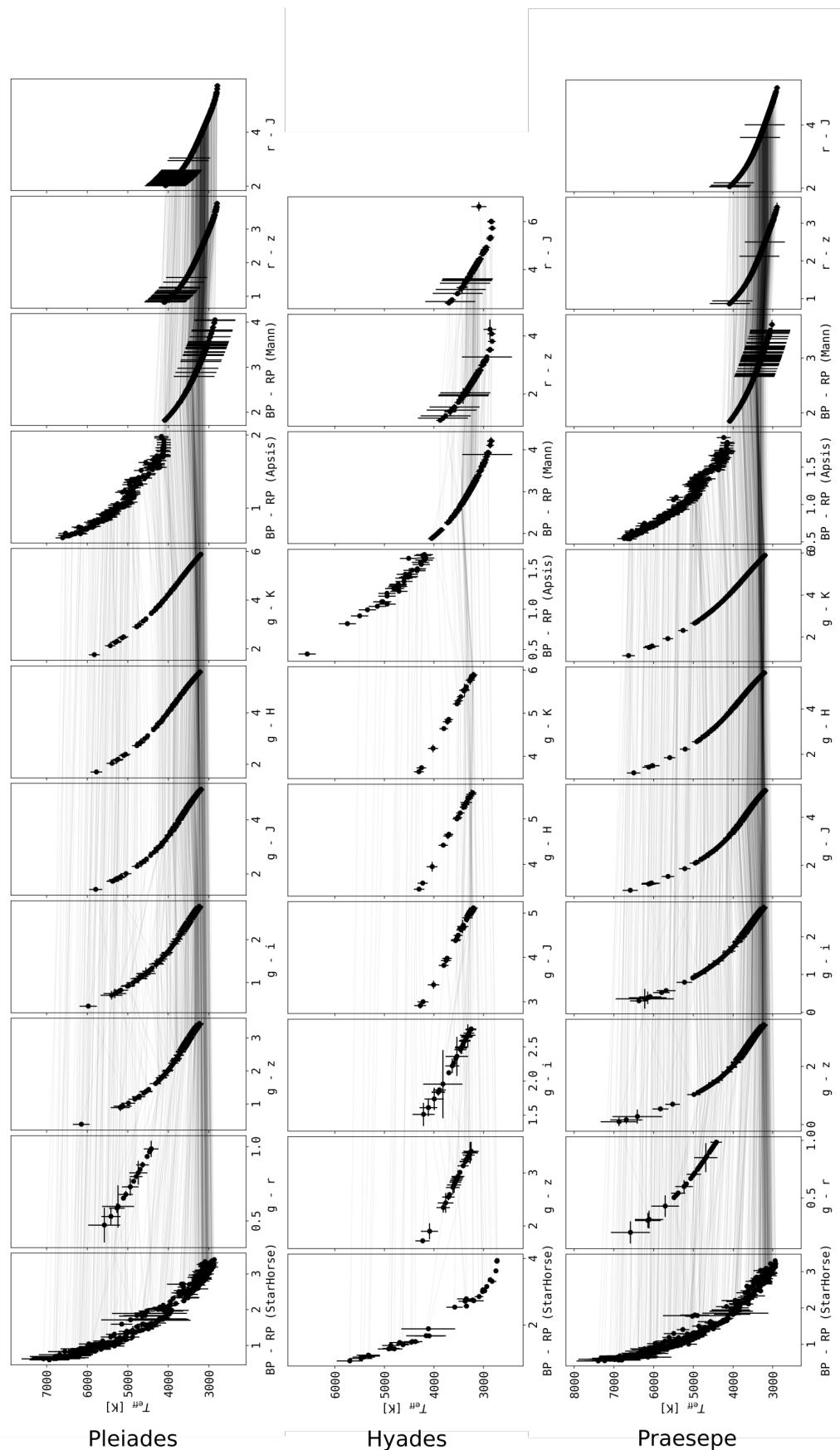
We applied several methods and color-temperature relations (CTRs) to determine robust  $T_{\text{eff}}$  (Figs. 2 and 3). We used CTRs from Boyajian et al. (2013) and Mann et al. (2016) (erratum to Mann et al. 2015),  $T_{\text{eff}}$  derived from Gaia DR2 using the StarHorse algorithm (Queiroz et al. 2018), and  $T_{\text{eff}}$  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  $g-z$ ,  $g-i$ ,  $g-r$ ,  $g-J$ ,  $g-H$ , 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).

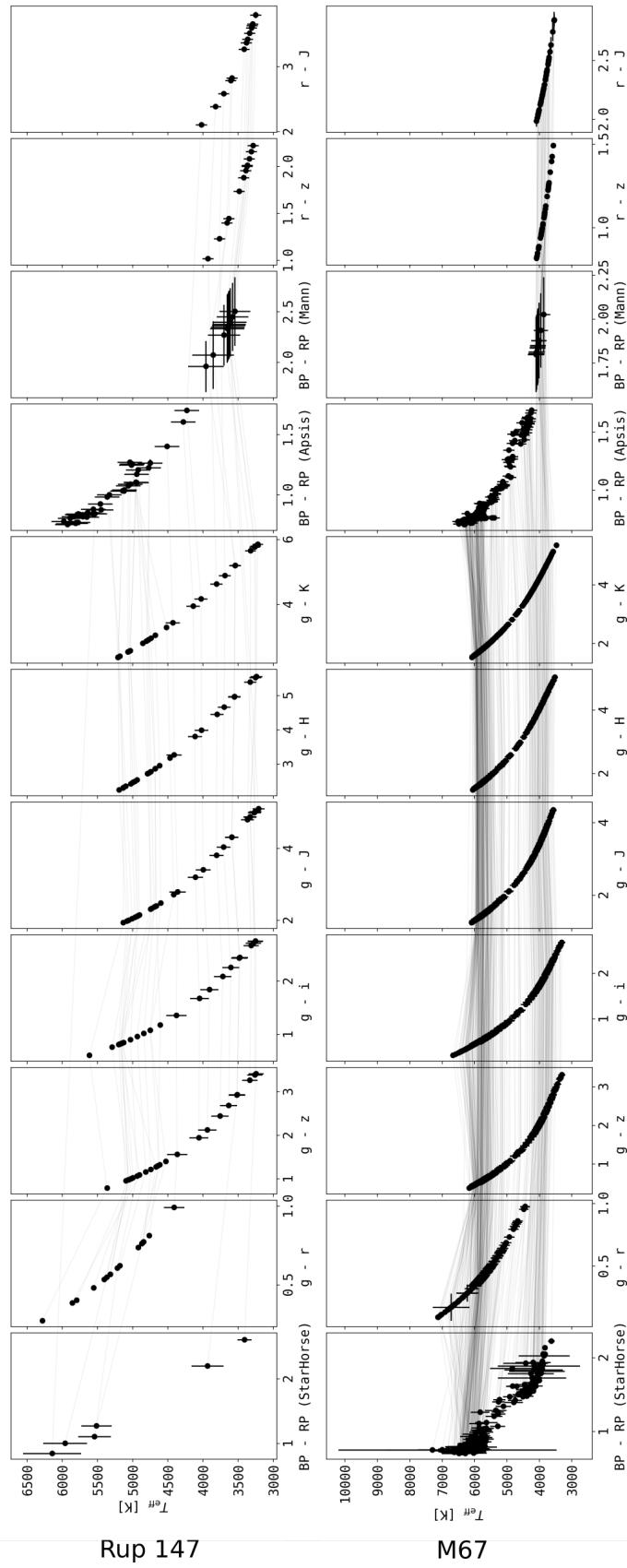
Mann et al. (2015) derived CTRs from absolutely calibrated spectra to which they fitted atmospheric models to obtain  $T_{\text{eff}}$ . Alternatively, they determined  $T_{\text{eff}}$  from long-baseline optical interferometry measurements using the bolometric flux. They noted transformations for SDSS/2MASS  $r - z$  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  $T_{\text{eff}}$  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).

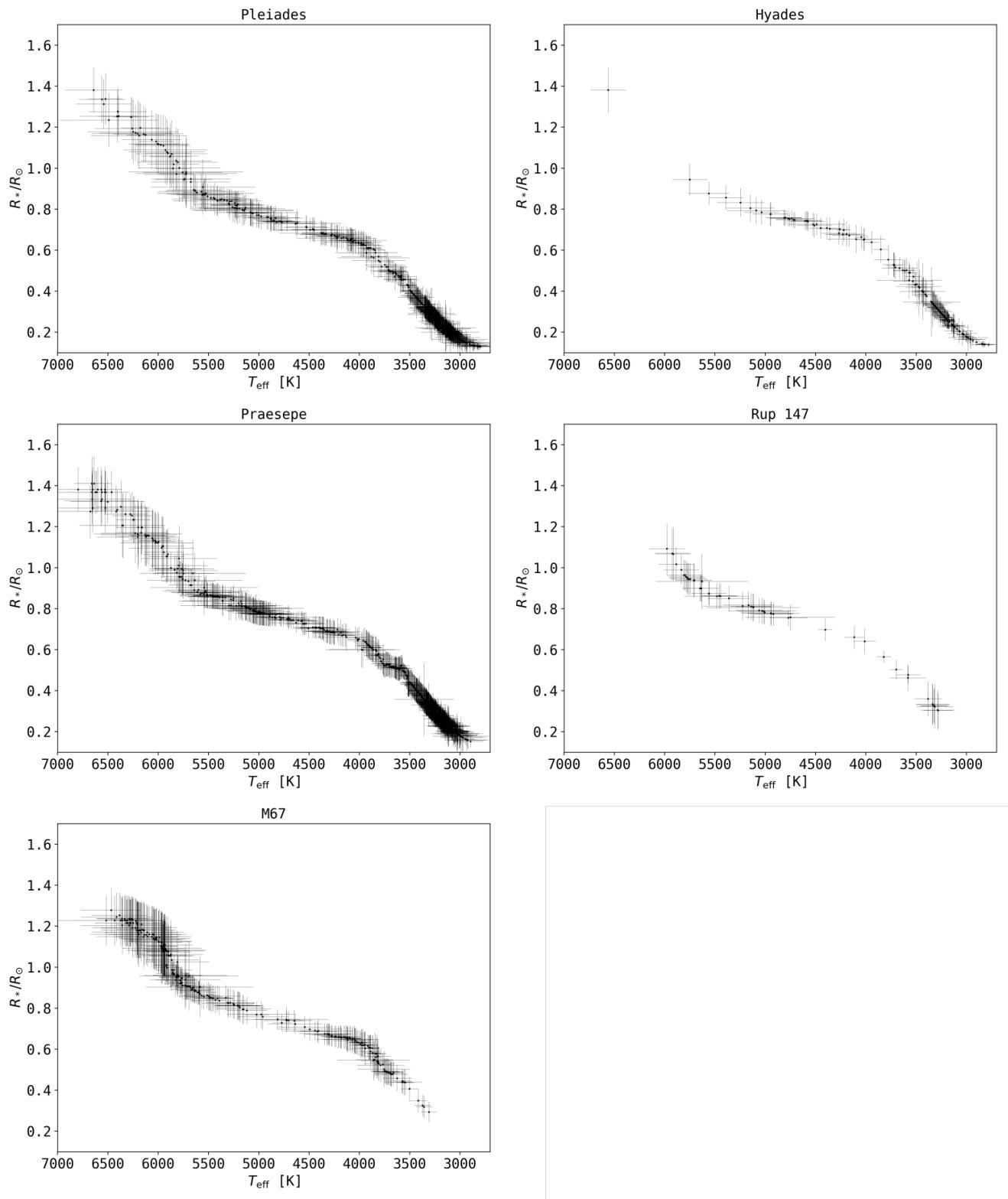
Gaia DR2 published  $T_{\text{eff}}$  for over 160 million sources (Gaia Collaboration et al. 2018b). The typical uncertainty was quoted



**Fig. 2.** Empirical color-temperature relations applied to high probability members in the Pleiades, the Hyades, and Praesepe. Individual stars are connected by lines between sub-plots to illustrate differences in the relations.



**Fig. 3.** Empirical color-temperature relations applied to high probability members in Ruprecht 147, and M67. Description as in Fig. 2.



**Fig. 4.**  $T_{\text{eff}}$  –  $R_*$  relation for all clusters in this study.

at 324 K, but it is lower for stars above  $\sim 4100$  K and below  $\sim 6700$  K, so that we adopt 175 K which is above the quoted root-mean-squared error in this  $T_{\text{eff}}$  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  $T_{\text{eff}}$  from each, and draw a more reliable median value. Targets that were lacking sufficient photometric data to derive  $T_{\text{eff}}$ , 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  $T_{\text{eff}}$  was greater than 10 %. Only targets that were assigned a  $T_{\text{eff}}$  were searched for flares.

### 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  $T_{\text{eff}}$  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  $T_{\text{eff}}$ , 15 % in  $R_*$ , and 0.09 dex in [Fe/H]. We interpolated between stars from the catalog to our derived  $T_{\text{eff}}$ , 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 (Schmidt 2014; 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; ?, 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 as appears in Pecaut & Mamajek (2013). We then combined stellar radii  $R_*$ ,  $T_{\text{eff}}$ , and spectra to projected bolometric luminosities  $L_{\text{bol},*}$ , and projected luminosities in the Kepler band  $L_{Kp,*}$  (Shibayama et al. 2013; Ilin et al. 2019). Uncertainties on  $L_{Kp,*}$  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 AltaiPony<sup>2</sup> to automatically detect and characterize flares in our sample. The code base relied on K2SC<sup>3</sup> (Aigrain et al. 2016) to remove instrumental and astrophysical variability from K2 light curves. We did not use the de-trended light curves available on MAST<sup>4</sup>, but used K2SC to de-trend light curves from the re-processed final data release. We clipped outliers at  $3\sigma$  iteratively, as compared to the original work, where outliers were clipped at  $5\sigma$  (Aigrain et al. 2016). After de-trending, the flare finder algorithm searched for continuous observing periods, defined as being 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 the iterative procedure that (Schmidt et al. (2020) in prep.) applied to TESS light curves. The finder iteratively clipped excursions from the median value at  $3\sigma$ . After each iteration, outliers were cut down to the current median value. Either after convergence, or 50 iterations, the resulting median value was adopted. With this median as quiescent flux, flare candidates were identified with the same procedure as during the median value calculation, but we additionally required at least three consecutive data points to fulfill the  $3\sigma$ -criterion. Flare candidates were merged into single candidate events if they were less than four data points apart. For each of these candidates 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 a 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 eventually dominated the photometric noise.

The Kepler flare sample has shown to be difficult to treat in a fully automated way. Without manual vetting, the event samples remain significantly contaminated (Yang & Liu 2019). As K2 was subject to severe technical difficulties, the expected contamination rate was expected to be even higher. 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 a few hours or passages of bright solar system objects (SSOs) had to be masked accordingly or fitted with an additional sinusoidal component to the K2SC-treated time series. 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 Table 2 includes explanatory flags and notes on the excluded targets. **Here is some room for SkyBot notes.**

### 3.2. Kepler flare energies

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 to some degree, with, to date, no robust predictor of that temperature: 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 9000 – 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,

<sup>2</sup> [altaipony.readthedocs.io](https://altaipony.readthedocs.io)

<sup>3</sup> [github.com/OxES/k2sc](https://github.com/OxES/k2sc)

<sup>4</sup> [archive.stsci.edu/prepds/k2sc/](https://archive.stsci.edu/prepds/k2sc/)

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. 10, and Lin et al. 2019, in particular), although they just different methods to infer  $E_{flare}$ .

### 3.3. 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  $\alpha$  and  $\beta$  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, and were power law distributed as an ensemble (Wheatland 2004). While the MMLE was computationally efficient and was useful to obtain first results (see Appendix D), only the predictive distribution allowed us to fit for  $\alpha$  and  $\beta$  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 the 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  $\epsilon$  that a flare with  $ED$  or  $E_{Kp}$  above some value  $S_2$  would occur within a time

period  $\Delta T$ :

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

$C$  was the normalisation constant,  $M$  was the number of events,  $T$  the total observation time.  $\Gamma$  contained the prior distribution for  $\alpha$ , and  $S_1$  denoted the detection threshold above which all flares were detected.  $\pi$  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  $\epsilon$  we derived  $\beta$  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  $\alpha$  the results from the MLE and Markov Chain Monte Carlo (MCMC) sampling from the posterior distribution were consistent within uncertainties (see Appendix D). However, the MCMC method allowed us to fit for both  $\epsilon$  and  $\alpha$  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. F.1 in Appendix F). We chose our prior to reflect this result: Starting from a uniform prior for  $\alpha$  and  $\epsilon$ , we found a Gaussian distribution to be an excellent fit to the posterior distribution for  $\alpha$  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 open clusters for flares, and measured their energies and occurrence rates. We found 2918 flares. We fitted power law relations to the flare frequency distributions (FFD) of stars binned by age, and  $T_{eff}$ . 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, 2 500-3 000 K), stellar flaring activity at a given age was higher for cooler stars.

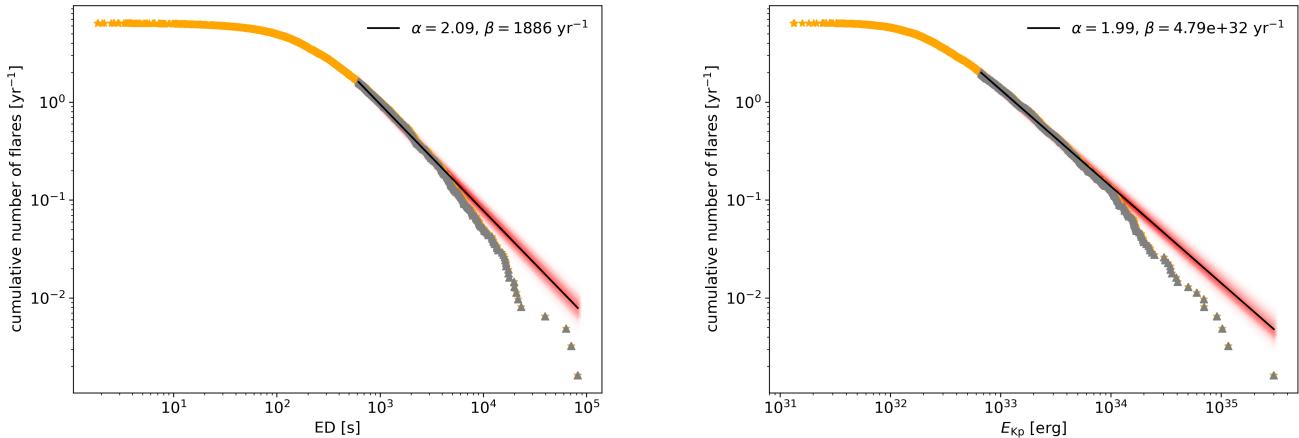
### 4.1. Flare frequency distributions

We fitted power law parameters for  $\alpha$  and  $\beta$  to the full sample FFDs in  $E_{Kp}$  and  $ED$  space by sampling from the joint posterior distribution (Eq. 4). We chose uninformative priors for both  $\alpha$  and  $\epsilon$ .

The detection threshold in any FFD was not a unique function of  $E_{Kp}$  or  $ED$ , but depends on the flares' amplitudes and

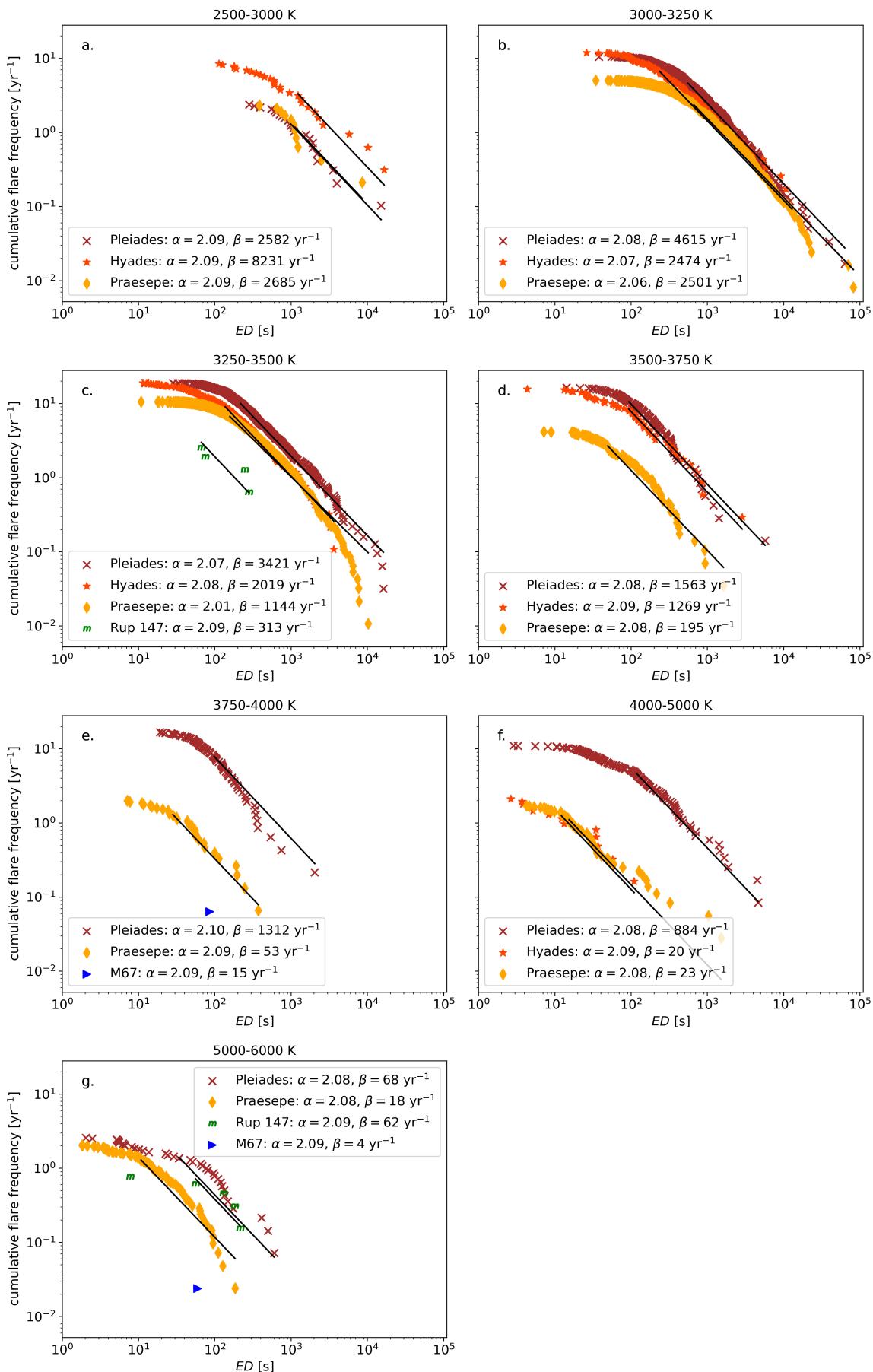
**Table 2.** Selection of confirmed flare candidates detected in open clusters observed by Kepler/K2, sorted by amplitude  $a$ . The full table is available on CDS. Uncertainties are noted in parentheses.

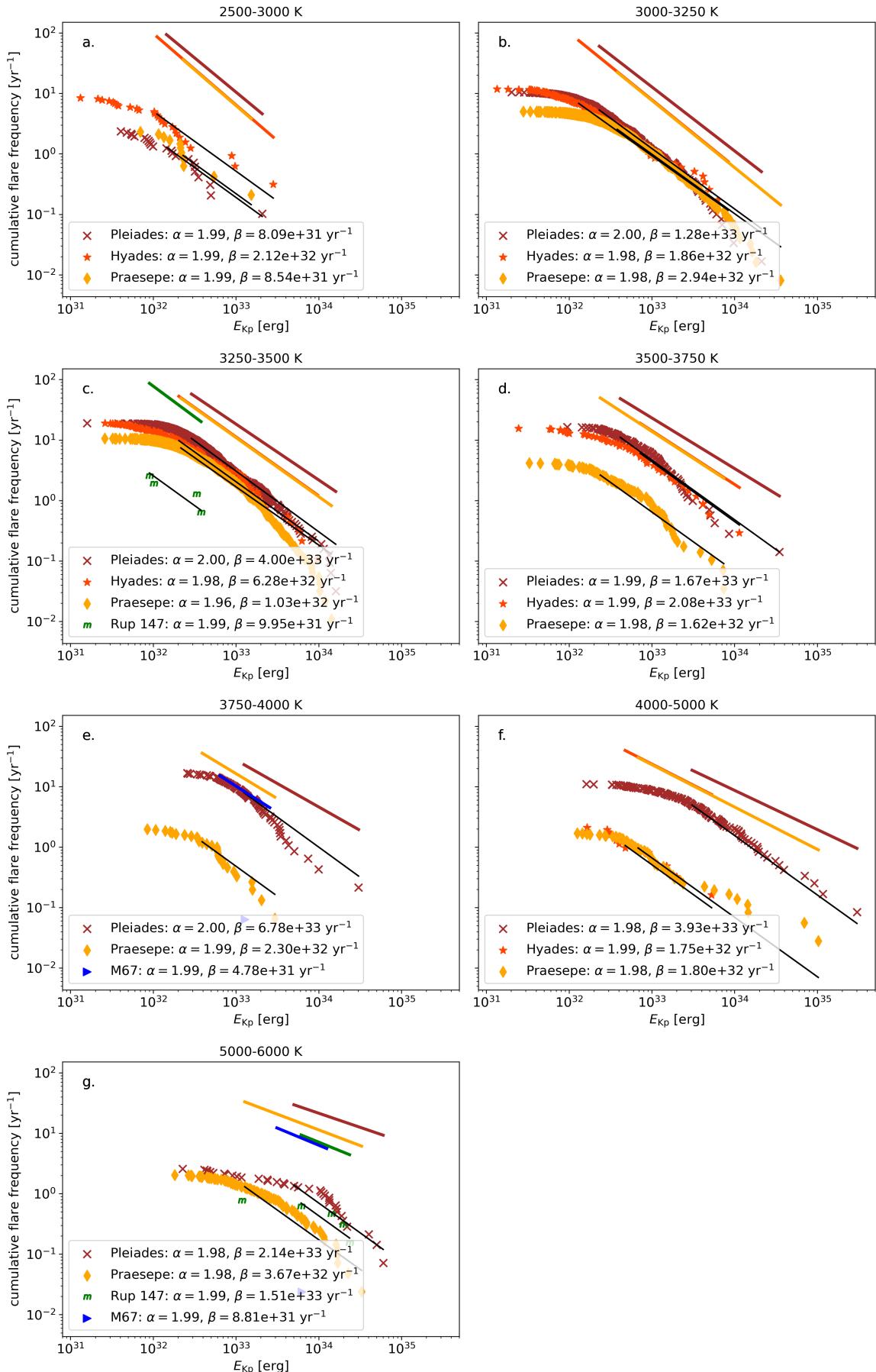
EPIC	C	cluster	$c_0$	$c_1$	$a$	$T_{\text{eff}}$ [K]	$ED$ [s]	$L_{\text{bol},*}$ [erg/s]	$L_{\text{Kp}}$ [erg/s]
211079830	4	Pleiades	105984	105993	15.330194	3097(87)	63340(63)	$8.29(3.34)10^{29}$	$3.32(1.34)10^{29}$
210720772	4	Pleiades	107181	107184	9.674757	3104(86)	19901(7)	$8.66(3.45)10^{29}$	$3.48(1.38)10^{29}$
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)	$1.90(0.65)10^{30}$	$7.78(2.66)10^{29}$
211994910	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)	$2.72(1.10)10^{30}$	$1.12(0.45)10^{30}$

**Fig. 5.** FFD (scatter) in  $ED$  (left panel) and energy (right panel) and respective power law fit (black line) to the full sample of flare candidates. The full FFD is shown in orange, the portion used for the fit is overplotted in grey. The red shade is a randomly drawn sample from the posterior distribution.

durations. Since it was computationally not feasible to perform the injection 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. To a first approximation to a detection threshold, we chose to use only the portion of the FFD for the fit, where all flaring stars contributed, and doubled the resulting 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. Consequently the high-energy tail of the FFD would also be incomplete. To arrive at consistency

**Fig. 6.** FFDs (scatter) in  $ED$  and respective power law fits (black lines).



**Fig. 7.** FFDs (scatter) in  $E_{Kp}$ , power law fits to the data (black lines), and predictions from the Davenport et al. (2019) flaring-age-mass parametrization (colored lines).

with a powerlaw at a 5% significance level using a Kolmogorov-Smirnov as suggested by Wheatland (2004) by choosing ever higher low-energy cutoffs, we would have had to exclude the majority of flares. The power law exponent in these cases would have approached  $\alpha \sim 2.4$  (using only about 320 flares out of 2918). The absolute value of  $\alpha$  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  $T_{\text{eff}}$  bins suffered from the same incompletenesses.

We fitted a Gaussian distribution to the posterior distribution for  $\alpha$  from the full sample. The values for the full sample FFDs in  $E_{\text{Kp}}$  and  $ED$  space (Fig. 5) are summarized in Table 4. 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  $T_{\text{eff}}$  bins and constructed the FFDs cluster by cluster (Figs. 6, and 7). The fitted Gaussian distributions 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 are summarized in Table 3.

#### 4.2. $\beta_s$

Relative flaring activity levels were best described by  $\beta_s$ , 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)  $\beta_s$  is a measure of flaring activity in which the different energy budgets of stars are controlled for. We could therefore use  $\beta_s$  to compare across both  $T_{\text{eff}}$  and age at the same time. Fig. 8 can also be interpreted as a synthesis of the FFDs presented in Fig. 6. Overall,  $\beta_s$  declined with age in all investigated  $T_{\text{eff}}$  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  $\alpha$  for each component we inferred  $\beta_{s,A} \approx 1900 \text{ yr}^{-1}$  and  $\beta_{s,B} \approx 2200 \text{ yr}^{-1}$ , consistent with  $\beta_s$  for the Pleiades, or Hyades/Praesepe within uncertainties.

#### 4.3. Flaring luminosity FA

The energy released in flares was inferred using our derived stellar luminosities. It declines with age for every  $T_{\text{eff}}$  bin considered for both the total luminosity and relative to the quiescent flux (Fig. 9).

$FA$  is the luminosity in flares in the Kepler band. We can relate this to the quiescent bolometric luminosity of the star when we define the fractional flare luminosity  $FA$  (similar to PaperI):

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

We determined  $L_{\text{bol,*}}$  from  $R_*$  and  $T_{\text{eff}}$ , as described in Sec. 2.3. In Fig. 9 we computed the median and standard deviation  $FA$  for every  $T_{\text{eff}}$  bin.  $FA$  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  $FA$  values across age than across  $T_{\text{eff}}$ .

#### 4.4. Hyades and Praesepe

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 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. E.1 in the Appendix). In this temperature regime, the overwhelming 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

We found several flare candidates in members of M67 and Rup 147. But upon close inspection all but the events that occurred on four stars either turned out to be false positives, or occurred 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 two flares in M67 on two K dwarfs. 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 these stars, the multiplicity status was unknown. We found that the mass range of these stars as calculated from the uncertainties on their radii (Eker et al. 2018) was large enough that the four stars in question could in principle be binary stars with undetected mid-M dwarf companions (Table 4.5). 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 dwarf having 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  $T_{\text{eff}}$  bins.

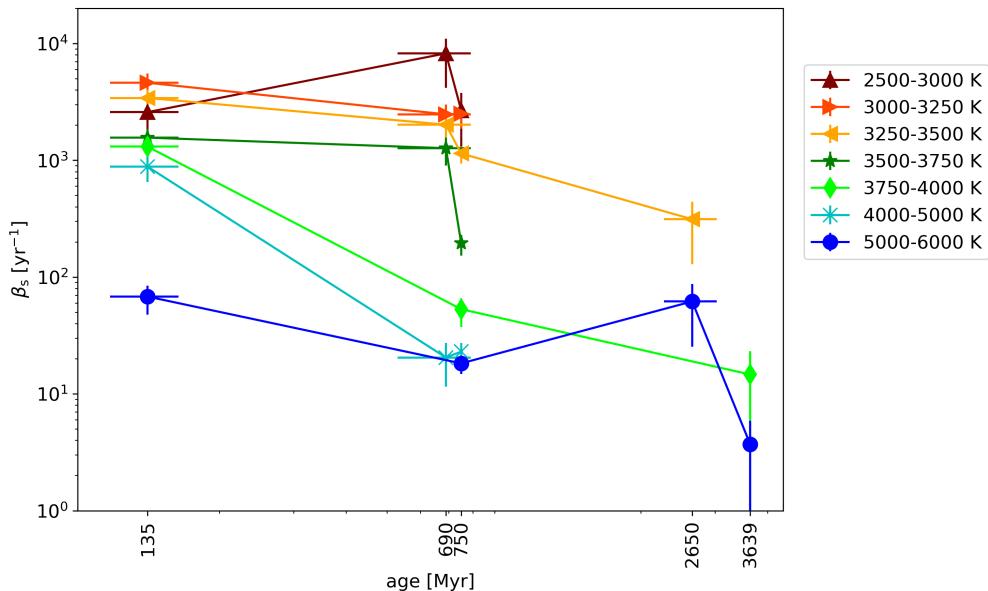
Here is room for some notes on Martti's SkyBot.

### 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. 2019a) we found encouraging consistency but also some noteworthy discrepancies that we could not always trace back to its cause. We found poor agreement 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  $\alpha$ , and on the

**Table 3.** Summary of flaring  $\beta$  of all clusters and  $T_{\text{eff}}$  bins in  $E_{\text{Kp}}$  and  $ED$  distributions.

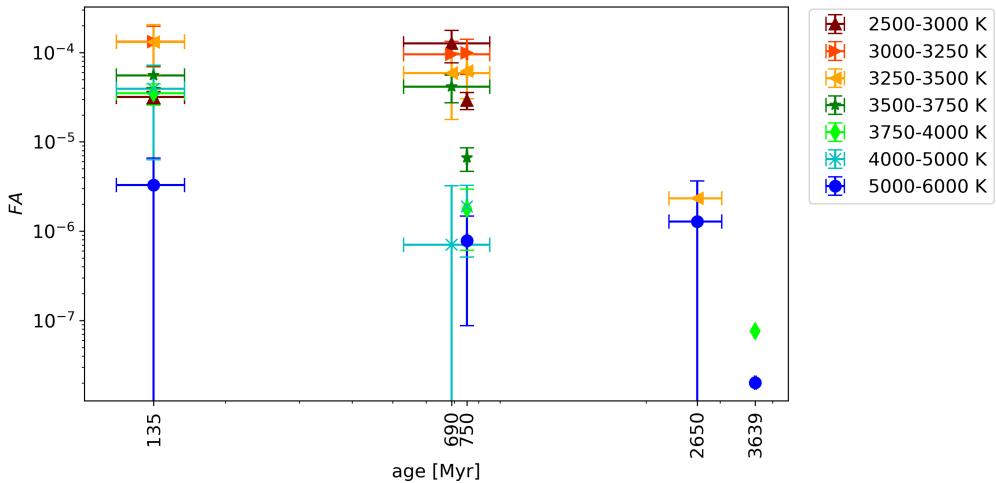
		$\alpha_s$	$\beta_s$	$n_s$	$\alpha_{\text{erg}}$	$\beta_{\text{erg}}$	$n_{\text{erg}}$
2500-3000	Hyades	2.09 (0.03)	8230 (4053) 2777	27	1.99 (0.03)	2.1 (15.7) 1.9 · 10 <sup>32</sup>	27
	Pleiades	2.09 (0.03)	2581 (1185) 845	23	1.99 (0.03)	0.8 (6.0) 0.7 · 10 <sup>32</sup>	23
	Praesepe	2.09 (0.03)	2684 (1635) 1088	11	1.99 (0.03)	0.9 (6.5) 0.8 · 10 <sup>32</sup>	11
3000-3250	Hyades	2.07 (0.03)	2474 (662) 523	138	1.98 (0.03)	1.9 (12.6) 1.6 · 10 <sup>32</sup>	138
	Pleiades	2.08 (0.03)	4615 (1176) 924	623	2.00 (0.02)	1.3 (7.2) 1.1 · 10 <sup>33</sup>	623
	Praesepe	2.06 (0.03)	2501 (543) 512	621	1.98 (0.02)	2.9 (16.4) 2.5 · 10 <sup>32</sup>	621
3250-3500	Hyades	2.08 (0.03)	2018 (491) 400	176	1.98 (0.03)	0.6 (4.3) 0.5 · 10 <sup>33</sup>	176
	Pleiades	2.07 (0.03)	3420 (748) 611	598	2.00 (0.02)	0.4 (2.3) 0.3 · 10 <sup>34</sup>	598
	Praesepe	2.01 (0.03)	1144 (204) 171	987	1.96 (0.02)	1.0 (4.5) 0.8 · 10 <sup>32</sup>	987
3500-3750	Rup 147	2.09 (0.03)	312 (183) 127	4	1.99 (0.03)	1.0 (7.7) 0.9 · 10 <sup>32</sup>	4
	Hyades	2.09 (0.03)	1269 (371) 294	53	1.99 (0.03)	2.1 (15.3) 1.8 · 10 <sup>33</sup>	53
	Pleiades	2.08 (0.03)	1563 (370) 300	116	1.99 (0.03)	1.7 (11.6) 1.5 · 10 <sup>33</sup>	116
3750-4000	Praesepe	2.08 (0.03)	195 (42) 35	119	1.98 (0.03)	1.6 (11.1) 1.4 · 10 <sup>32</sup>	119
	M67	2.09 (0.03)	14 (14) 8	1	1.99 (0.03)	0.5 (4.2) 0.4 · 10 <sup>32</sup>	1
	Pleiades	2.10 (0.03)	1312 (363) 288	78	2.00 (0.03)	0.7 (5.2) 0.6 · 10 <sup>34</sup>	78
4000-5000	Praesepe	2.09 (0.03)	53 (15) 12	30	1.99 (0.03)	2.3 (17.1) 2.0 · 10 <sup>32</sup>	30
	Hyades	2.09 (0.03)	20 (8) 6	13	1.99 (0.03)	1.8 (14.0) 1.6 · 10 <sup>32</sup>	13
	Pleiades	2.08 (0.03)	884 (232) 184	131	1.98 (0.03)	0.4 (2.9) 0.3 · 10 <sup>34</sup>	131
5000-6000	Praesepe	2.08 (0.03)	22 (5) 4	61	1.98 (0.03)	1.8 (13.4) 1.6 · 10 <sup>32</sup>	61
	M67	2.09 (0.03)	3 (3) 2	1	1.99 (0.03)	0.9 (8.2) 0.8 · 10 <sup>32</sup>	1
	Pleiades	2.08 (0.03)	68 (20) 16	36	1.98 (0.03)	2.1 (17.8) 1.9 · 10 <sup>33</sup>	36
3750-4000	Praesepe	2.08 (0.03)	18 (3) 2	85	1.98 (0.03)	0.4 (2.7) 0.3 · 10 <sup>33</sup>	85
	Rup 147	2.09 (0.03)	61 (36) 25	5	1.99 (0.03)	1.5 (13.0) 1.4 · 10 <sup>33</sup>	5

**Fig. 8.** Flare  $\beta_s$  vs. age grouped by  $T_{\text{eff}}$ .

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. 10). Overall



**Fig. 9.** FA for flares above the shared energy threshold ( $3.34 \cdot 10^{32}$  erg) as determined for the full FFD in  $E_{Kp}$  in Fig. 5.

**Table 4.** Summary of FFD parameters and power law fits to the full sample of all clusters in  $E_{Kp}$  and  $ED$  space.  $\alpha$ : power law exponent.  $n_{\text{tot}}$ : number of flares in the FFD.  $n_{\text{fit}}$ : number of flare used to fit the power law.

	$ED$	$E_{Kp}$
$\alpha$	$2.09 (0.03)$	$1.99 (0.03)$
$\beta [\text{yr}^{-1}]$	$1886 (548)$	$4.79 (38.01) \cdot 10^{32}$
$n_{\text{tot}}$	3937	3937
$n_{\text{fit}}$	989	1224

**Table 5.** Mass budget of flaring stars in M67 and Rup 147 within uncertainties on radius. The hypothetic binary pairs were calculated assuming that the primary mass was the smallest possible within  $1\sigma$  of the uncertainty on their radii. Median SpT: The spectral type of the target if it was a single star. Binary: The hypothetic binary pair with the highest possible mass ratio.

cluster	EPIC	median SpT	binary
M67	211420952	K9	K6.5 + M5.5
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

we believe that the differences in the results were rooted in a combination of astrophysical properties like age, mass and rotation speed, and the influence of selection criteria on the respective samples.

The flare frequency distributions of two 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).

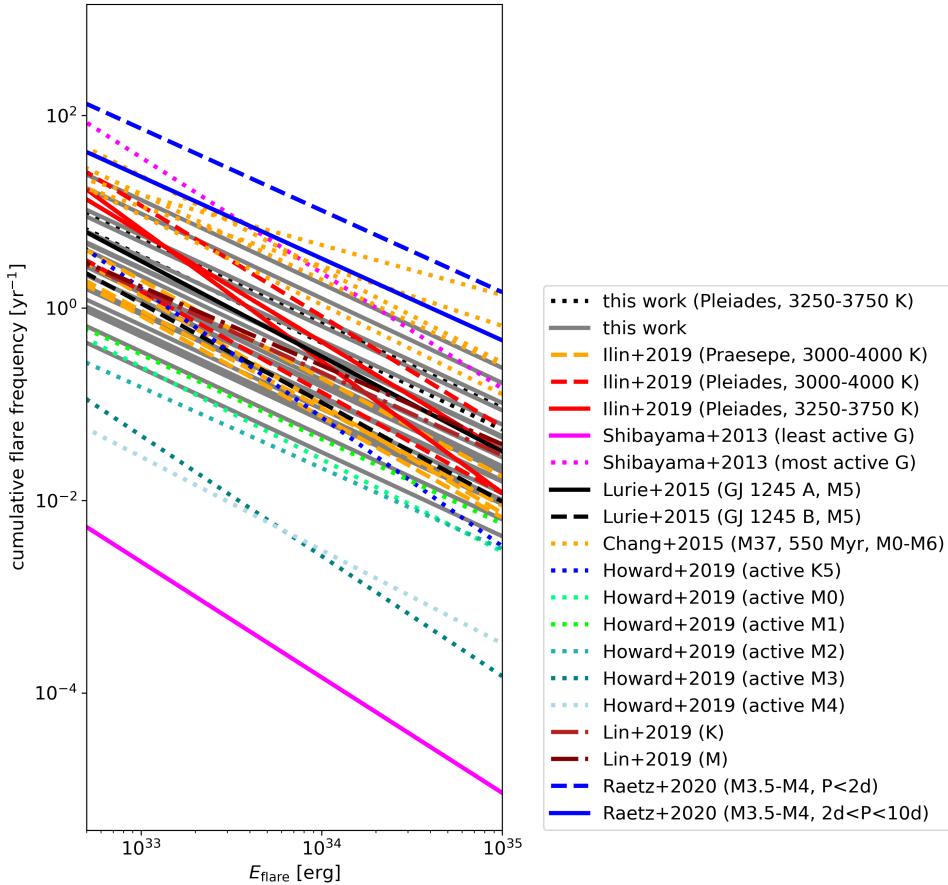
The frequency of superflares at  $10^{34}$  erg in the most active G-dwarfs and Sun-like stars in Kepler was once in 10–100 days, and every 800 years on average Sun-like stars (Shibayama et al. 2013). Benchmarking on the flare detected on a K1 dwarf in M67 in the G to early K bin (5000-6000 K), and accounting 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 10 years. Doing the same for the Pleiades stars yielded that ZAMS G to K dwarfs flare once in 140 days at  $10^{34}$  erg. Young G-K stars therefore corresponded roughly to the active G dwarfs in Shibayama et al. (2013) and our solar-age G-K dwarfs appeared more active than in their results.

Howard et al. (2019a) monitored superflares on cool stars with bolometric energies above  $10^{33}$  erg and up to  $10^{36}$  erg. They found power law exponent values around  $\sim 2$  resolved by spectral types. The activity levels for spectral types K5 to M4 were on average lower than in our sample, which could be explained by the overall older age of the stars in their sample. However, they only included stars that exhibited flares (active stars) into their FFDs, whereas we also included the observing time of stars where no flares had been detected into our estimates of occurrence rates. A comparison of the distribution of rotation rates in our sample and the EvryFlare catalog (Howard et al. 2019b) was out of scope for this study.

Photometric flares observed by the MMT 6.5 telescope (Hartman et al. 2008) in the  $\sim 550$  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. 2019b). We found  $\beta_s$  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  $\beta_s$  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 M3.5-M4 dwarfs appeared more active than the results for the Pleiades in Ilin et al. (2019) in the 3250 – 3750 K range. Our revised results remained consistent with Ilin et al. (2019) (Fig. 10). Both samples consisted of flares with periods below 10 d. Rotation periods  $P_{\text{rot}}$  were given for 100% of the sample in Raetz et al. (2020), and for  $> 85\%$  in our respective sub-sample (see Fig. E.1 in the Appendix for the distribution of  $P_{\text{rot}}$ ). One possible reason for the discrepancy could have been that the M3.5-M4 dwarfs in Raetz et al. (2020) targeted stars at a different age than the Pleiades at which the stars of similar



**Fig. 10.** Comparison of FFDs found in different flare studies. Grey lines: Flare frequency distributions from this work. Red and orange dashes: K2 long cadence light curves study of Pleiades and Praesepe open clusters, respectively, in four  $T_{\text{eff}}$  bins from 3000 to 4000 K each (PaperI). Magenta lines and dots: Kepler superflares on the most and least active G dwarfs, respectively (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). Orange dots: Flare study based on MMT survey of the  $\sim 550$  Myr old open cluster M37 (Chang et al. 2015). Dots in shades of blue: Evryscope all-sky flare search on late K to mid M dwarfs (Howard et al. 2019a). Dash-dotted lines: K2 long-cadence study of K and M dwarfs within 200pc and 100pc, respectively (Lin et al. 2019). 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).

rotation speeds show higher flaring activity. Another possible explanation was that the discrepancy arose from the 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 peculiarly active stars. A resolution of this discrepancy must also take into account that the results for our Praesepe 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  $\alpha$  and  $\beta$  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 power law fits with given mass and age in Fig. 7 alongside our results. The activity level in our sample appeared on average an order of magnitude lower than predicted. 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. We found that the model also failed to predict the relative differences in flaring activity between the clusters observed within individual  $T_{\text{eff}}$  bins (Fig. 7).

## 5.3. Universality of $\alpha$

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  $\alpha$  in our sample were almost precisely 2 in  $ED$  space, and somewhat below 2 in  $E_{\text{Kp}}$ , consistent with previous work (Fig. F.1 in the Appendix). The determination of  $\alpha$  usually faces multiple challenges making it difficult to assess whether the spread in  $\alpha$  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 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. 2020) for TESS. However, GP regression, which was used to de-trend the light curves, was in itself to costly to repeat it 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 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).

#### 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 all FFDs with  $\geq 50$  flares were consistent with a power law distribution, we found no evidence for truncation in any of the  $T_{\text{eff}}$ -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  $T_{\text{eff}}$  ranges anchoring the age to the membership of our targets in five open clusters. We found flaring activity as measured by the power law intercept  $\beta_s$  in  $ED$  space 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  $T_{\text{eff}}$  and stellar luminosities. Keeping only targets with well-determined mass and age we proceeded to search 2256 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 2256 stars in five open clusters, and found a total of 2918 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  $\alpha$  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  $T_{\text{eff}}$  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 discrepancies noted in this work and elsewhere, 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. (2016a); 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  $\text{flux}/\text{flux\_error} \geq 10$  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: 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  $\alpha$  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:

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

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  $\alpha$  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  $\alpha$  to account for this bias:

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

Using the MMLE method on the full sample of flares in  $E_{Kp}$  and  $ED$  space we obtained  $\alpha_{\text{erg}} = 1.85$  and  $\alpha_s = 1.95$ , respectively, indicating a marginally flatter power law than the predictive model ( $\alpha_{\text{erg}} = 1.99$ ,  $\alpha_s = 2.09$ ).

## Appendix E: Rotation and flaring

More energetic flares can be expected from faster rotating stars (Candelaresi et al. 2014; Doorsselaere et al. 2017; Yang et al. 2017). However, the famous 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 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  $T_{\text{eff}}$  (see Fig. 8). In Fig. E.1 we show rotation periods derived from K2 light curves for the Pleiades (Rebull et al. 2016b), the Hyades and Praesepe (Douglas et al. 2019), to illustrate the  $P_{\text{rot}}$  distributions that correspond to our  $T_{\text{eff}}$  bins at fixed ages.

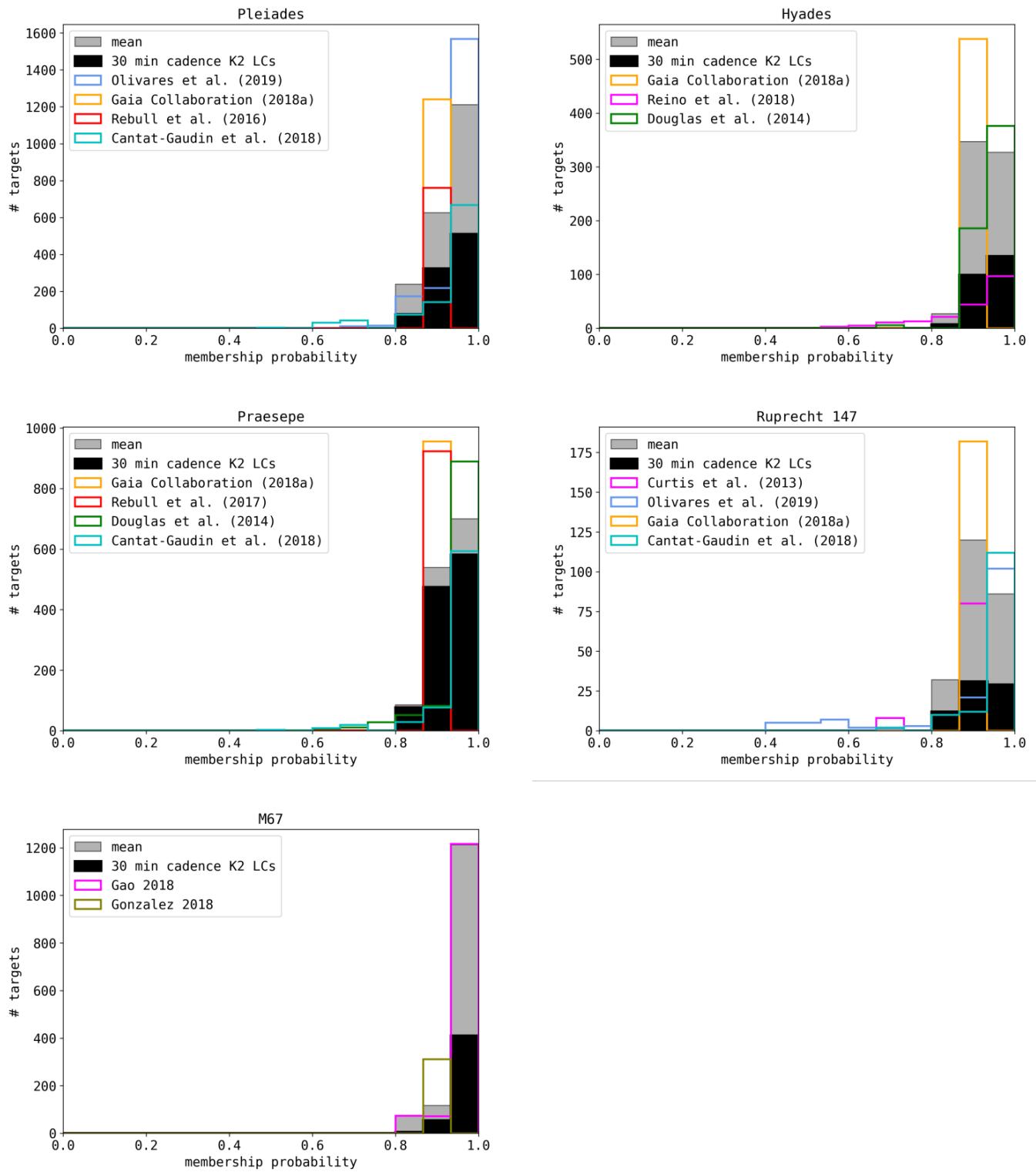
## Appendix F: Universality of $\alpha$

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

**Table A.1.** Membership catalogs overview. No distance are given for Hyades we adopted individual distances for all members.

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. (2016a)	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

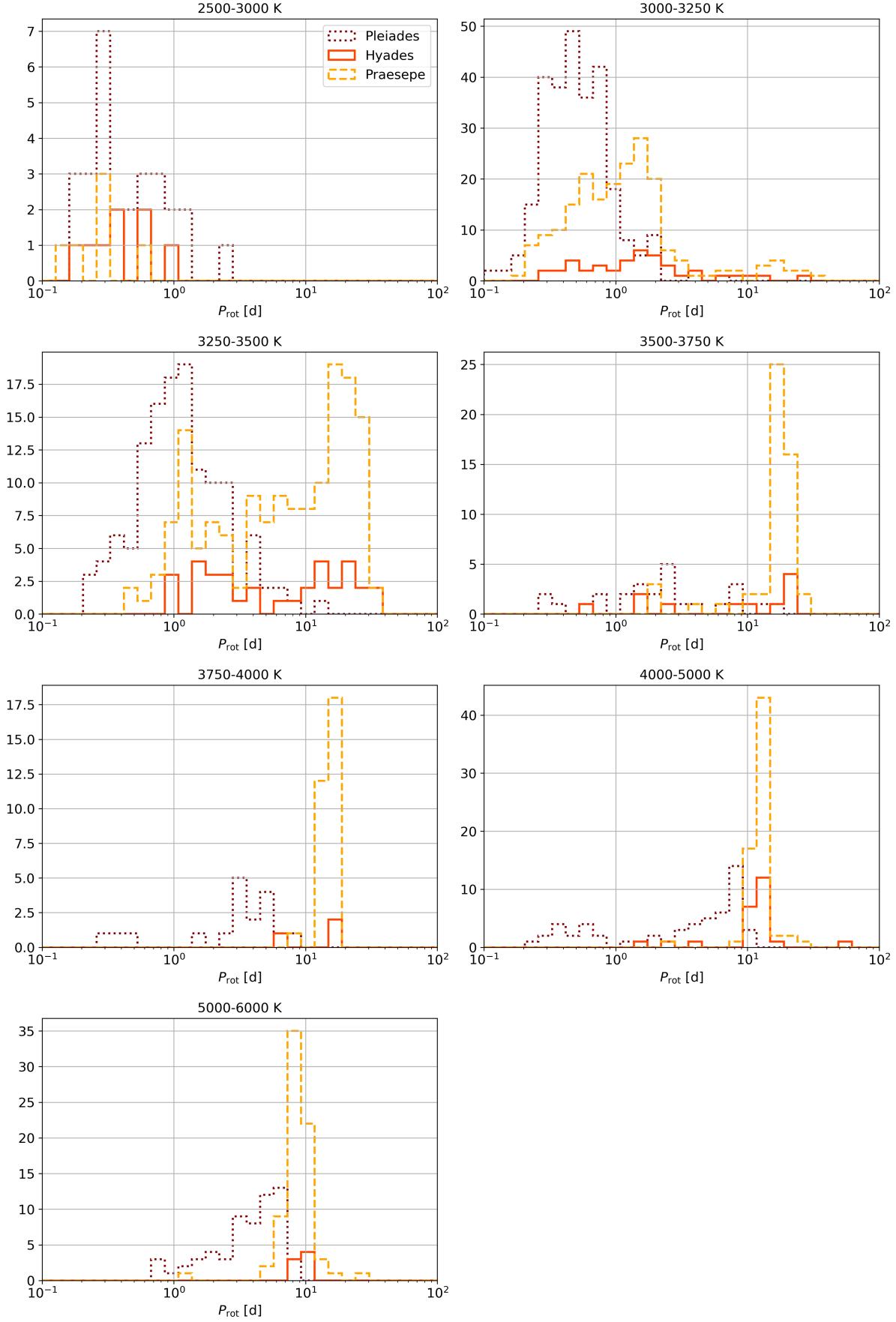
**Notes.** DANCe: DANCe membership study project. (1) Positions for Hyades were propagated to epoch 2000 using Gaia proper motions.

**Fig. A.1.** OC membership histograms and selected targets.

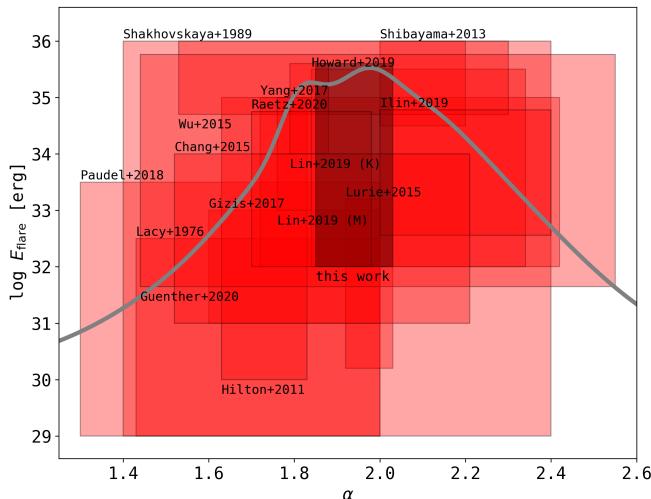
**Table B.1.** Non-exhaustive literature overview over OC parameters.

cluster	source	distance [pc]	age [Myr]	[Fe/H]
<b>Pleiades</b>	<b>adopted in this work:</b>	135.6	$135 \pm 25$	$-0.037 \pm 0.026$
Pleiades	Bossini et al. (2019) <sup>a</sup>		$86.5 \pm 6$	
Pleiades	Cantat-Gaudin et al. (2018)	135.6		
Pleiades	Gossage et al. (2018)		$135 \pm 25$	
Pleiades	Yen et al. (2018)	126.3	$141.3 \pm 170$	
Pleiades	Chelli and Duvert (2016)	139		
Pleiades	Netopil et al. (2016)			-0.01
Pleiades	Dahm (2015)		$112 \pm 5$	
Pleiades	Scholz et al. (2015)	130	120	
Pleiades	Conrad et al. (2014)			$-0.037 \pm 0.026$
Pleiades	Melis et al. (2014)	136		
Pleiades	Bell et al. (2012)	135	125	
<b>Hyades</b>	<b>adopted in this work:</b> <sup>c</sup>		$690 \pm 160$	$0.13 \pm 0.02$
Hyades	Gaia Collaboration (2018)		$690 \pm 160$	
Hyades	Gossage et al. (2018)		680	
Hyades	Liu et al. (2016)			$\pm 0.02$
Hyades	Netopil et al. (2016)			0.13
Hyades	Taylor and Joner (2005)			$0.103 \pm 0.008$
Hyades	Cummings et al. (2005)			$0.146 \pm 0.004$
Hyades	Salaris et al. (2004)		650	0.15
Hyades	Perryman et al. (1998)		$625 \pm 50$	
Hyades	Martin et al. (1998)		$650 \pm 70$	
<b>Praesepe</b>	<b>adopted in this work:</b>	185.5	$750 \pm 3$	0.16
Praesepe	Bossini et al. (2019)		$750 \pm 3$	
Praesepe	Cantat-Gaudin et al. (2018)	185.5		
Praesepe	Gossage et al. (2018)		590	
Praesepe	Yen et al. (2018)	183	$794 \pm 253$	
Praesepe	Netopil et al. (2016)			0.16
Praesepe	Scholz et al. (2015)	187	832	
Praesepe	Boesgaard et al. (2013)			0.12
Praesepe	Boudreault et al. (2012)	160	630	
Praesepe	Salaris et al. (2004)	175	650	
<b>Rup 147</b>	<b>adopted in this work:</b>	305	$2650 \pm 380$	$0.08 \pm 0.07$
Rup 147	Bragaglia et al. (2018)			$0.08 \pm 0.07$
Rup 147	Cantat-Gaudin et al. (2018)	305		
Rup 147	Gaia Collaboration (2018)	309	$1995 \pm 404$	
Rup 147	Torres et al. (2018)	283	$2650 \pm 380$	
Rup 147	Curtis (2016) <sup>b</sup>			$0.10 \pm 0.02$
Rup 147	Scholz et al. (2015)	270	1953	
Rup 147	Curtis et al. (2013)	300	$3125 \pm 125$	$0.07 \pm 0.03$
<b>M67</b>	<b>adopted in this work:</b>	908	$3639 \pm 17$	$-0.102 \pm .081$
M67	Bossini et al. (2019)		$3639 \pm 17$	
M67	Netopil et al. (2016)			0.03
M67	Scholz et al. (2015)		$3428 \pm 147$	
M67	Conrad et al. (2014)			$-0.102 \pm .081$
M67	Dias et al. (2012)	908	4300	
M67	Oïehag et al. (2011)	880	4200	0.02

**Notes.** <sup>(a)</sup> 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. <sup>(b)</sup> Curtis (2016) reanalysed HIRES spectra using an improved spectroscopic method as compared to Curtis et al. (2013). <sup>(c)</sup> We did not adopt a mean value for the Hyades distance because the cluster members are on average closer than 50 pc.



**Fig. E.1.** Rotation histograms for the cluster members that were searched for flares and had measured rotation periods  $P_{\text{rot}}$ . Rotation periods were taken from Douglas et al. (2019) for the Hyades and Praesepe, and from Rebull et al. (2016b) for the Pleiades. Rotation periods were available for 53 – 100% of the stars that we searched for flares with a median of 75%.



**Fig. F.1.** Literature overview over power law fits to FFDs. Red rectangles indicate the energy range in which flares were detected, and the range of values determined for the power law exponent  $\alpha$  including quoted uncertainties and superimposing the ranges for  $\alpha$  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. ilin2019 and this work are shown with a dashed 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  $\alpha$  from ground-based observations of M dwarfs. Lurie et al. (2015) determined  $\alpha$  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. (2019a) 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  $\sim 550$  Myr old M37 open cluster (Chang et al. 2015). Finally, (Günther et al. 2020) took a first look to  $\alpha$  as derived from stars observed during TESS Cycle 1. From their work we only use  $\alpha$  derived from stars with 20 or more flare detections.