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# Rotation and flares of M dwarfs with habitable zones accessible to TESS

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## Sample

- **112 M dwarfs** (spectral types K8 to M5)
- listed in TESS Habitable Zone Star Catalog (Kaltenegger et al. 2019)
- TESS can **detect planets in the full extent of the habitable zone**
- TESS mag.$\leqslant$11.5
- each star observed in multiple TESS sectors
  → **1276 light curves** (LCs) analyzed; example LC in Fig. 1

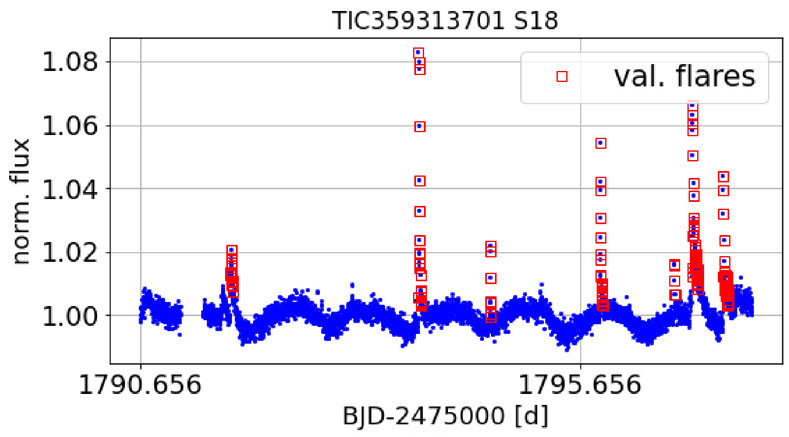


***Fig. 1:*** *Example of a TESS light curve showing rotational modulation (blue) and flares (red).*

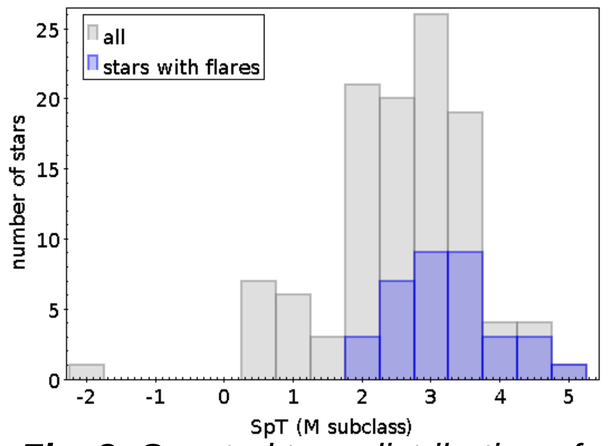


***Fig. 2:*** *Spectral type distribution of our sample. Numbers denote M subclasses, -2 stand for K8.*

## Analysis results

- **12 stars** (~11% of the sample) show **reliable rotation periods** (i. e. period search yielded consistent results for all TESS sectors of the star)
- **0.28 d** $\leqslant P_{rot} \leqslant$ **3.94 d**
- **35 stars** show flares (~31% of the sample); a total of **2532 flares** was detected
- 2138 flares occur on the 12 stars with reliable $P_{rot}$ - only 394 flares on others
- stars of SpT < M2 do not show any flares; **fraction of flaring stars higher for later M SpT subclasses** (cf. Fig. 2, Fig. 3)
- for most flares: **peak flare flux at inner HZ boundary** larger than the bolometric flux hitting the top of Earth's atmosphere (i. e. **(peak flare flux)/**$S_0$ **> 1**, cf. Fig. 4)
- binned flare frequency distribution (FFD) for earlier SpT range (M2.5-M3.5) shifted to higher flare energies w.r.t. later SpT range (M4.5-M5) (Fig. 5)
  → **flares on later M subtype stars are less energetic**
- **stars with reliable** $P_{rot}$ **have highest flare rates** (Fig. 3, Fig. 6)

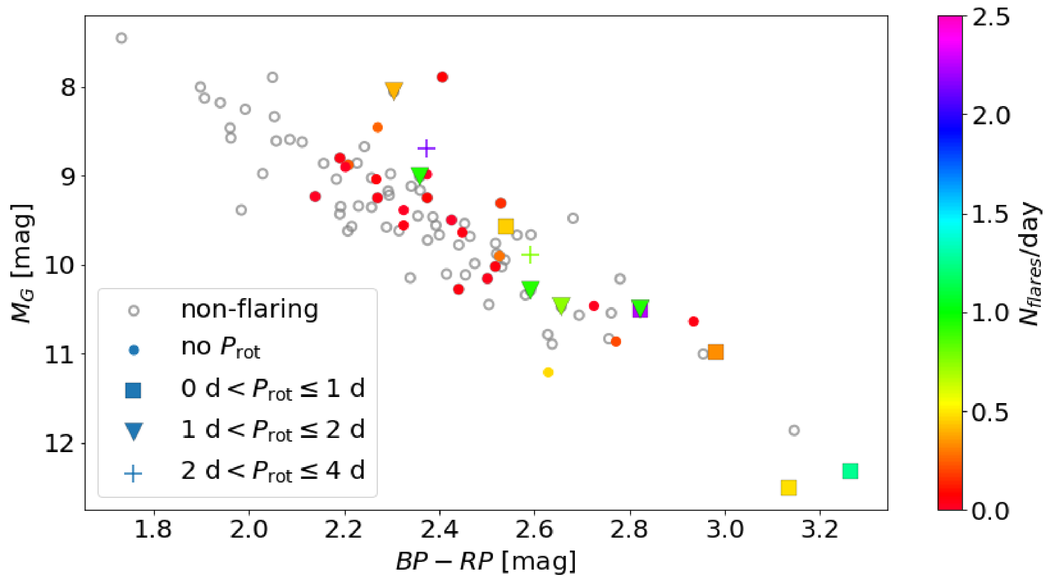


***Fig. 3:*** *Gaia HRD of the sample. Flare rates are color-coded for flaring stars.* $P_{rot}$ *ranges are represented by different markers. Stars with reliable* $P_{rot}$ *show higher flare rates. The fraction of flaring stars increases towards later M SpT subclasses (i. e. larger BP-RP indices)*

## Data Analysis

For details, see Stelzer at al. 2016 and Raetz et al. 2020

The algorithm can be briefly summarized as follows:

- **rotation period search** with 3 methods: Generalized Lomb Scargle Periodogram, Autocorrelation function and sine fit.
- **flare detection** based on flattened and cleaned LC with standard deviation $S_{flat}$: parts of original LC with **3 or more consecutive data points deviating** $>3\,S_{flat}$ from the LC's mean value are flagged as **potential flares**
  → detection bias: only flares with amplitudes $>3\,S_{flat}\cdot L_{qui}$ detectable ($L_{qui}$ = quiescent stellar luminosity in TESS band)
- flare candifates subject to several **validation criteria** (e. g. decay time has to be longer than raise time)
- **contamination factor** = $\dfrac{\Sigma \text{ flux of contaminating stars in aperture mask}}{\text{target flux}}$
- **energy completeness limit for flare detection** determined from FFD following Hawley et al. 2014

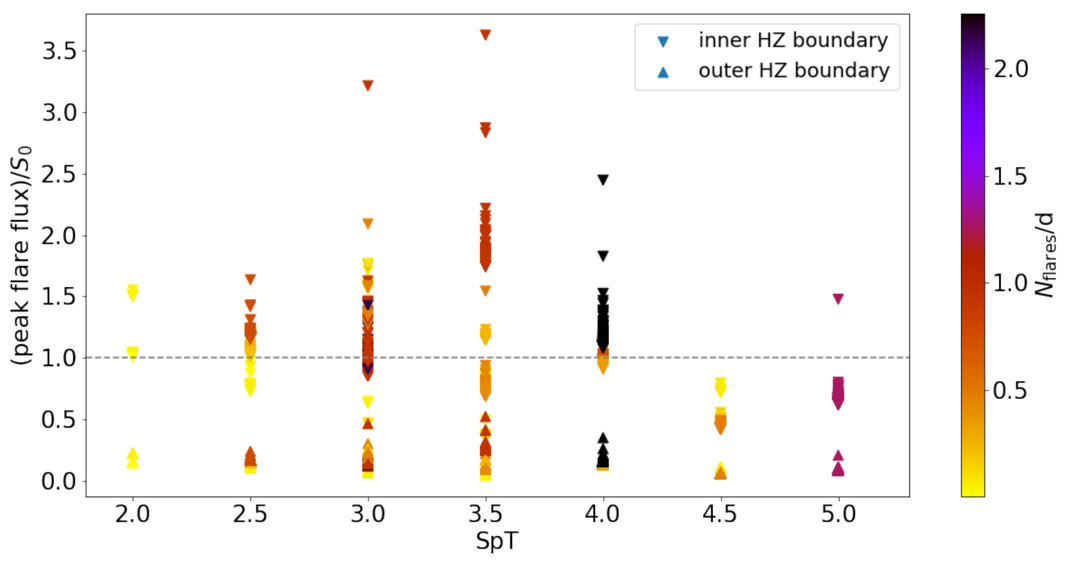


***Fig. 4:*** *Peak flare flux at the inner (Recent Venus) and outer (Early Mars) habitable zone boundary. Fluxes are normalized by the solar constant. The flare rate of each star is color-coded.*

## Summary

- later M SpT subclasses show higher fraction of flaring stars (Fig. 2, Fig. 3)
- atmospheres of potential exoplanets at inner HZ boundary are exposed to larger fluxes during flare events than Earth in quiescent solar state (Fig. 4)
- later M subtype stars show flares with lower energies (Fig. 5)
- stars with reliable $P_{rot}$ show higher flare rates (Fig. 3, Fig. 6)

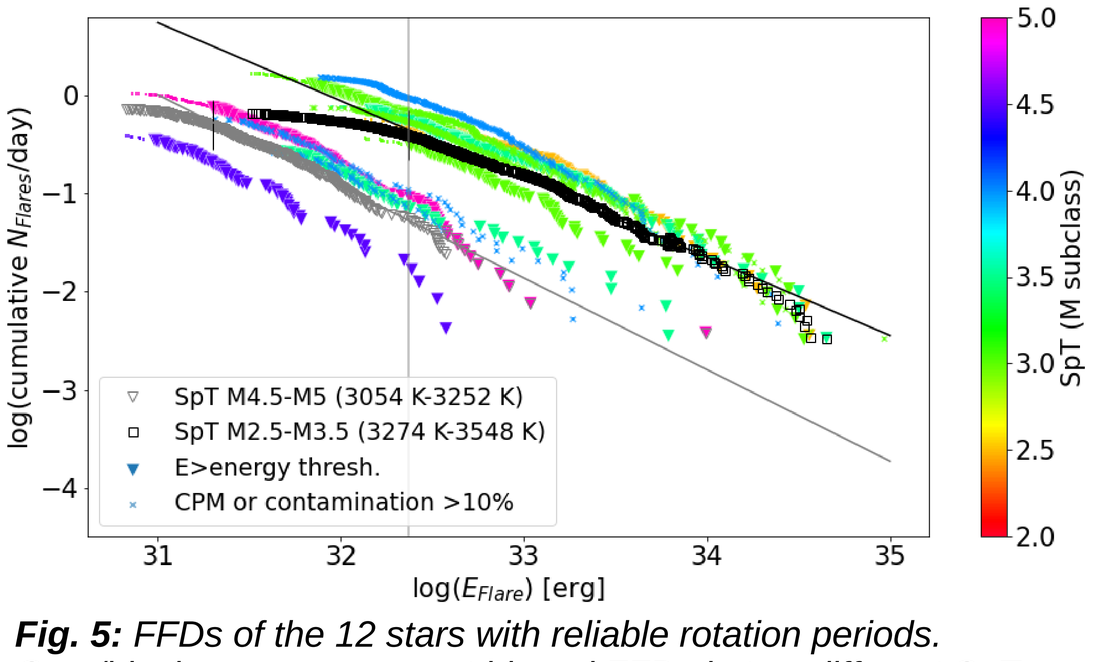


***Fig. 5:*** *FFDs of the 12 stars with reliable rotation periods. Grey/black curves represent binned FFDs in two different SpT ranges and fits using only data points above energy detection thresholds (vertical bars). Stars with common proper motion companions or a flux contamination >10% due to chance projections are not considered for the binned FFDs.*

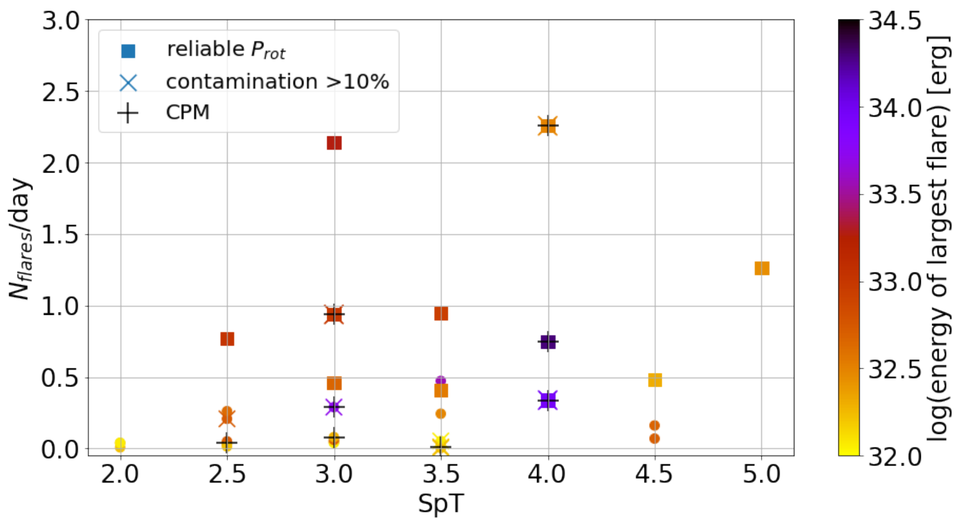


***Fig. 6:*** *Relation btw. flare rate and SpT.* $P_{rot}$ *Stars with reliable* $P_{rot}$ *show higher flare rates. Stars with PM companions are marked with '+', 'x' denotes those with contamination >10% (either CPM or chance projections)*