Observational signs of limited flare area variation and peak flare temperatures estimation in main-sequence flaring stars

Bezovec 2025 – Conference of Young Astronomers

Kamil Bicz, Robert Falewicz, Petr Heinzel, P. Preś, D. Moździerski,
A. Pigulski, D. Marchev, K. Kotysz, T. Atanasova, G. Yordanova, A. Georgiev

June 8, 2025 **Bezovec**

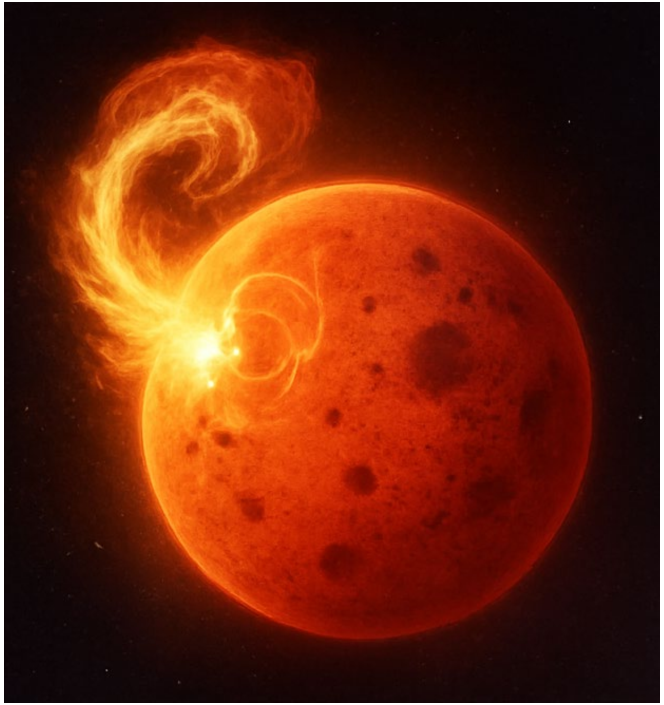
Stellar Magnetic Activity

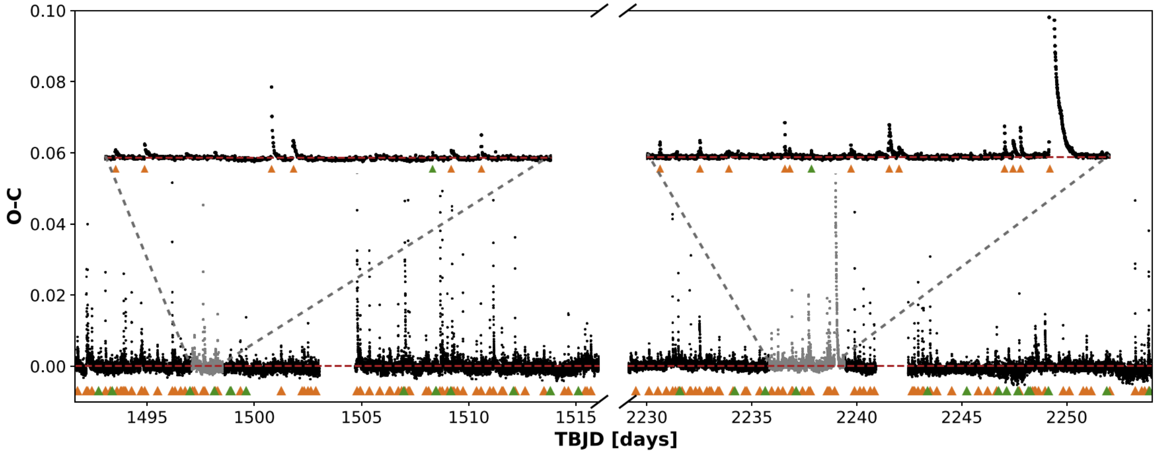
Stellar magnetic activity arises from strong magnetic fields, particularly in young, rapidly rotating late-type stars (e.g., K and M dwarfs – but not only!).

It leads to observable phenomena such as:

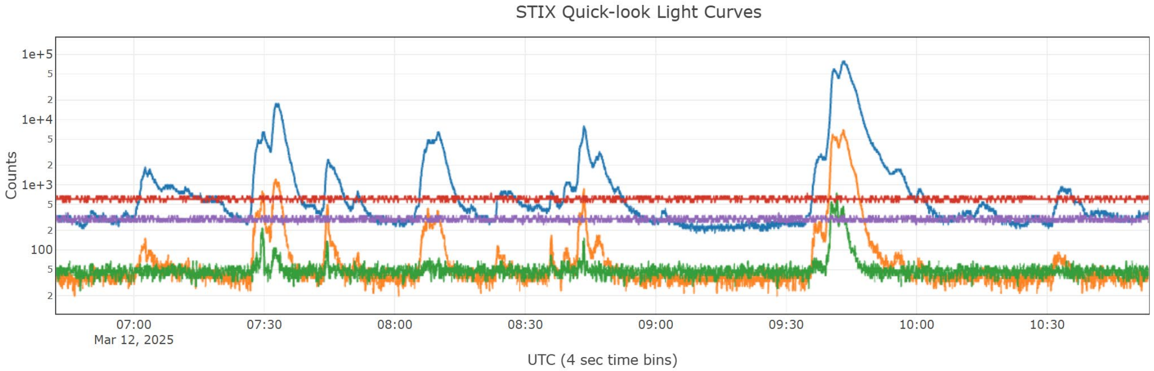
Flares: Sudden energy bursts across the whole electromagnetic spectrum from magnetic reconnection in the stellar corona.
Starspots: Cool, dark „surface” regions caused by magnetic flux inhibiting convection.
Enhanced Winds: Stronger, magnetized plasma outflows than the solar wind.
Magnetic Cycles: Periodic or chaotic changes in activity, similar to the Sun’s 11-year cycle.

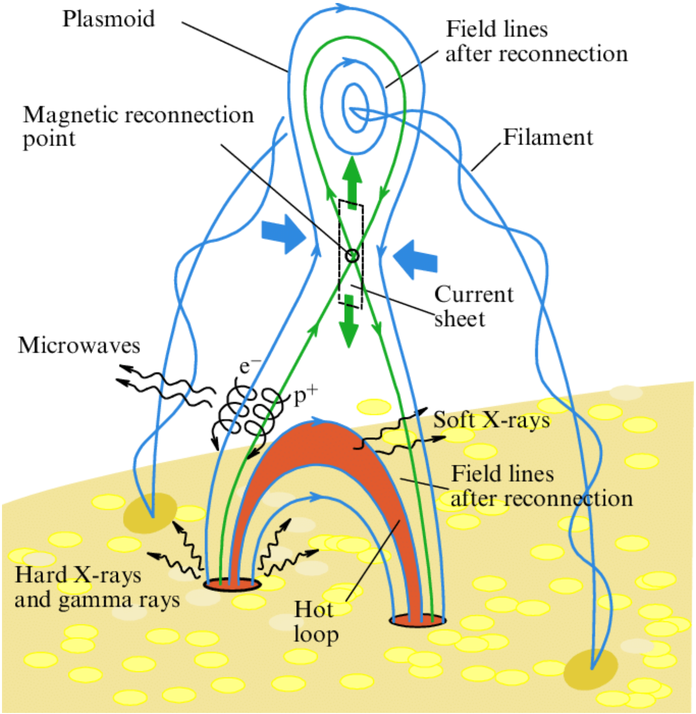
These features cause variability across wavelengths, especially in X-ray and radio domains.





Bicz et al., 2022





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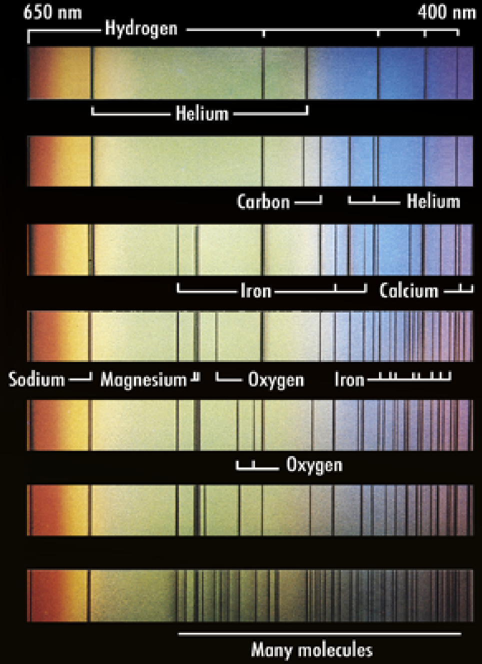
STELLAR CLASSIFICATION (MAIN-SEQUENCE)

SPECTRUM



CLASS	COLOR	TEMP. (C°)	HYDROGEN	SIZE(SOLAR R)	% OF ALL
O		>30,000	WEAK	>6.6	~0.00003%
B		9,700 - 30,000	MEDIUM	1.8 - 6.6	0.13%
A		7,200 - 9,700	STRONG	1.4 - 1.8	0.6%
F		5,700 - 7,200	MEDIUM	1.1 - 1.4	3%
G		4,900 - 5,700	WEAK	.9 - 1.1	7.6%
K		3,400 - 4,900	VERY WEAK	.7 - .9	12.1%
M		2,100 - 3,400	VERY WEAK	<.7	76.5%

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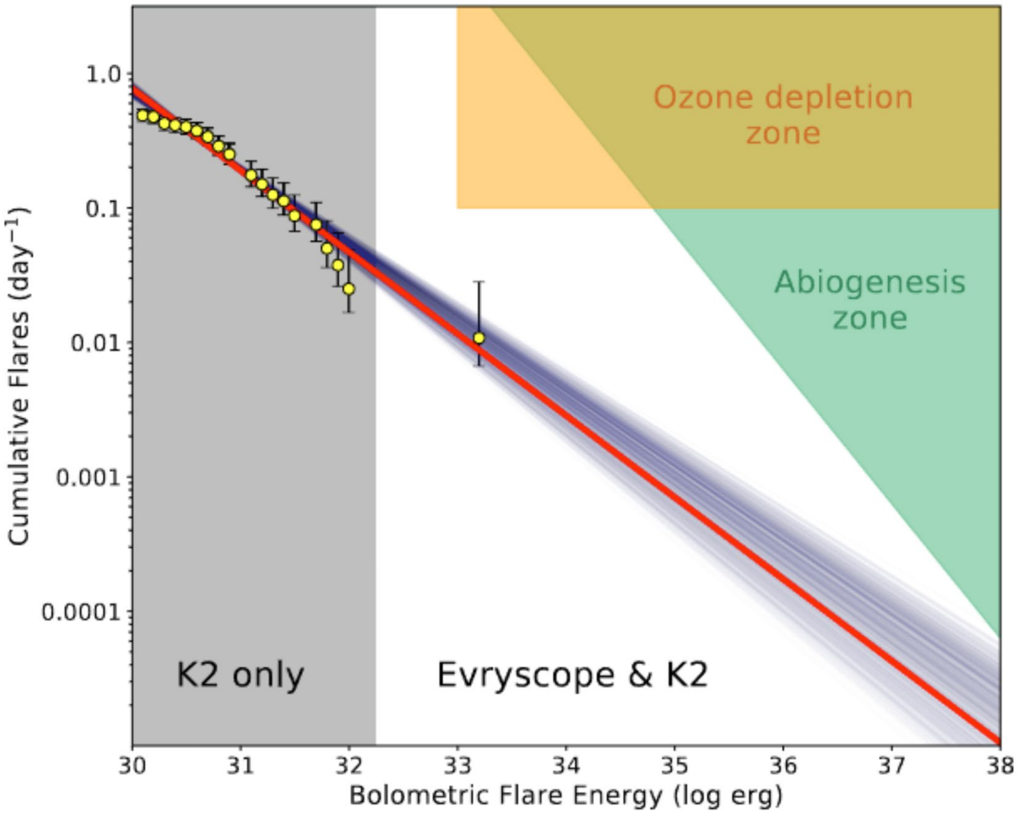

Glazier et al., 2020

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Astronomical Observatory University of Wrocław, Białków

Transiting Exoplanet Survey Satellite TESS

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EV Lac

$\mathrm{SpT} = \mathrm{M4Ve}$

$T_{\mathrm{eff}} = 3\,300 \pm 200\,\mathrm{K}$

$R = 0.34 \pm 0.01\,\mathrm{R}_\odot$

$M = 0.32 \pm 0.02\,\mathrm{M}_\odot$

$d = 5.05\,\mathrm{pc}$

$P_{\mathrm{rot}} = 4.359\,\mathrm{days}$

High flaring and spot activity

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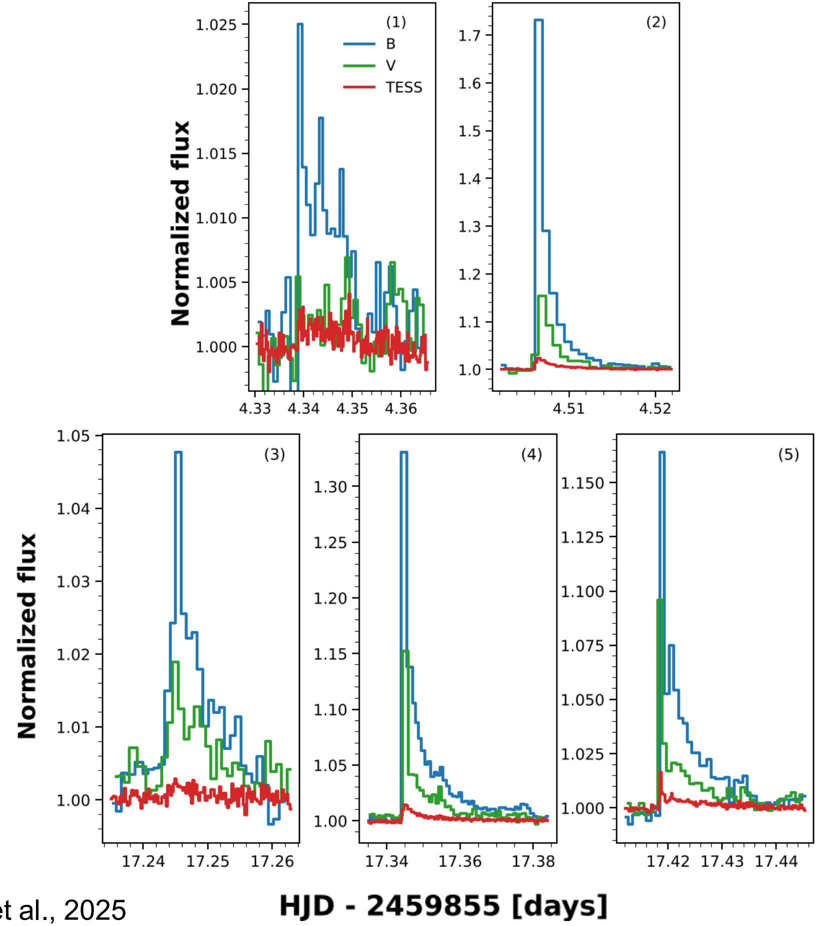
Astronomical Institute, University of Wrocław



Bicz et al., 2025

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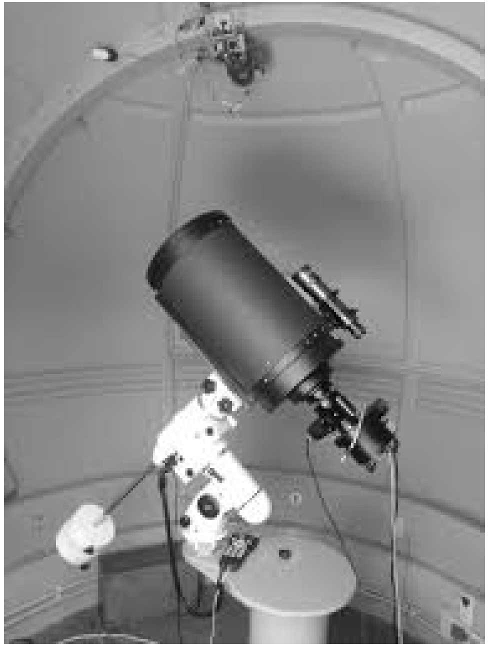
Shumen Astronomical Observatory
Bulgaria



Transiting Exoplanet Survey Satellite
TESS

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V374 Peg

$\mathrm{SpT} = \mathrm{M3.5Ve}$

$T_{\mathrm{eff}} = 3\,200 \pm 200\,\mathrm{K}$

$R = 0.31 \pm 0.01\,\mathrm{R}_{\odot}$

$M = 0.29 \pm 0.02\,\mathrm{M}_{\odot}$

$d = 9.1\,\mathrm{pc}$

$P_{\mathrm{rot}} = 0.4457572 \pm 0.0000002\,\mathrm{days}$

High flaring and spot activity

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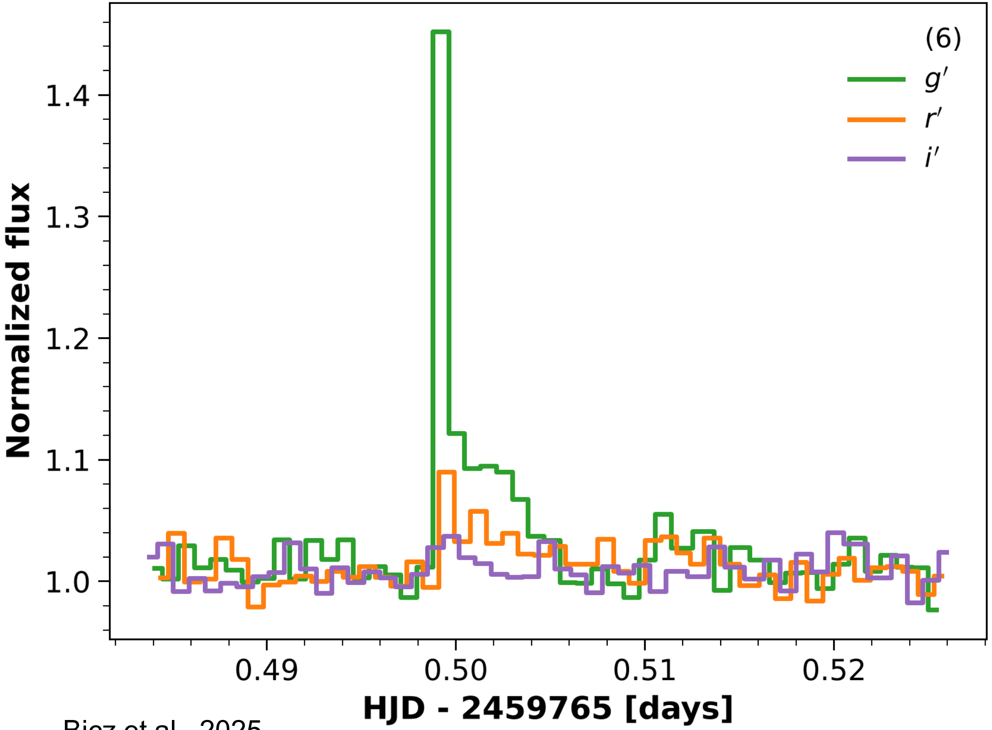
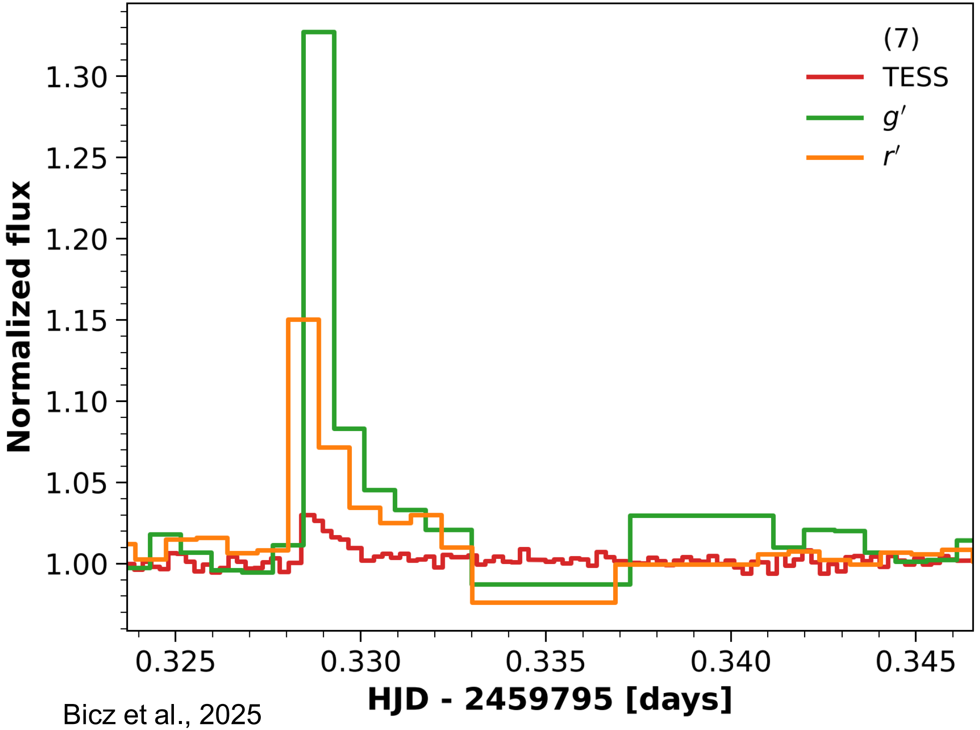


Bicz et al., 2025

GJ 1243

$$\mathrm{SpT} = \mathrm{M4Ve}$$
$$T_{\mathrm{eff}} = 3\,200 \pm 200\,\mathrm{K}$$
$$R = 0.27 \pm 0.01\,\mathrm{R}_{\odot}$$
$$M = 0.24 \pm 0.02\,\mathrm{M}_{\odot}$$
$$d = 11.95\,\mathrm{pc}$$
$$P_{\mathrm{rot}} = 0.59260 \pm 0.00021\,\mathrm{days}$$

High flaring and spot activity



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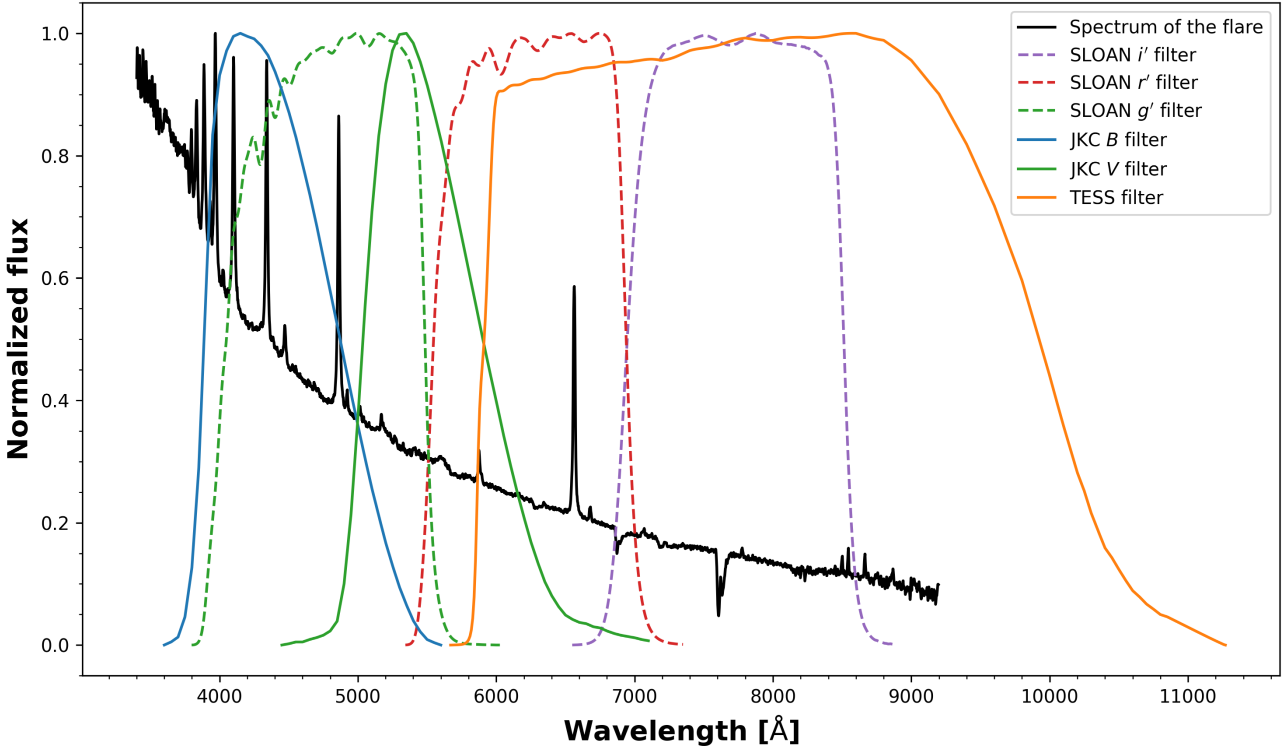

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Flare #	Observational night [YYYY-MM-DD/DD]	Observatory	Star	Used bandpasses	Bandpasses cadences [s]	TESS sector
1	2022-10-06/07	Białków	EV Lac	B, TESS	70, 20	57
2	2022-10-06/07	Białków	EV Lac	B, TESS	70, 20	57
3	2022-10-06/07	Białków	EV Lac	B, TESS	70, 20	57
4	2022-10-21/22	Białków	EV Lac	B, TESS	70, 20	57
5	2022-10-21/22	Białków	EV Lac	B, TESS	70, 20	57
6	2022-07-04/05	Shumen	V374 Peg	g', r'	70, 70	—
7	2022-08-02/03	Shumen	GJ 1243	g', r', TESS	70, 70, 20	54

Bicz et al., 2025

Flare #	TIC	Obs. time (UTC)	Peak T_{eff} [K]	SpT.
8	220433364	18-11-03 02:35	9 400 ± 300	M4Ve[1]
9	140045538	18-08-14 01:52	7 500 ± 500	M2Ve[2]
10	294750180	18-10-20 05:36	34 000 ± 2 300	M1Ve[2]
11	229807000	18-08-19 07:46	15 500 ± 400	M2.5Ve[3]
12	294750180	18-08-20 07:23	14 400 ± 400	M1Ve[2]
13	441398770	18-08-12 01:57	14 500 ± 3 000	M4.5Ve[4]
14	388857263	19-06-03 04:37	8 100 ± 400	M5.5Ve[5]
15	201919099	18-10-05 08:23	9 700 ± 300	K5Ve[2]

Notes. The date is expressed in a format YY-MM-DD hh:mm.
[1]Henry et al. (2002)
[2]Torres et al. (2006)
[3]Riedel et al. (2017)
[4]Joy & Abt (1974)
[5]Bessell (1991)

The Astrophysical Journal, 902:115 (14pp), 2020 October 20 https://doi.org/10.3847/1538-4357/abb5b4

CrossMark

EvryFlare. III. Temperature Evolution and Habitability Impacts of Dozens of Superflares Observed Simultaneously by Evryscope and TESS

Ward S. Howard[1], Hank Corbett[1], Nicholas M. Law[1], Jeffrey K. Ratzloff[1], Nathan Galliher[1], Amy L. Glazier[1], Ramses Gonzalez[1], Alan Vasquez Soto[1], Octavi Fors[1,2], Daniel del Ser[1,2], and Joshua Haislip[1]
[1] Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-3255, USA; wshoward@unc.edu
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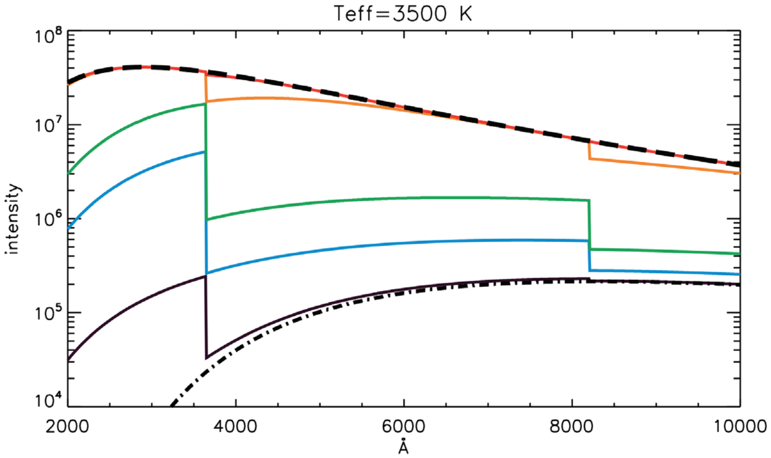
Received 2020 July 3; revised 2020 September 1; accepted 2020 September 1; published 2020 October 19

$$F_\lambda = \frac{A_{\rm fl} B_\lambda(T_{\rm fl})}{d^2}. \qquad (1)$$

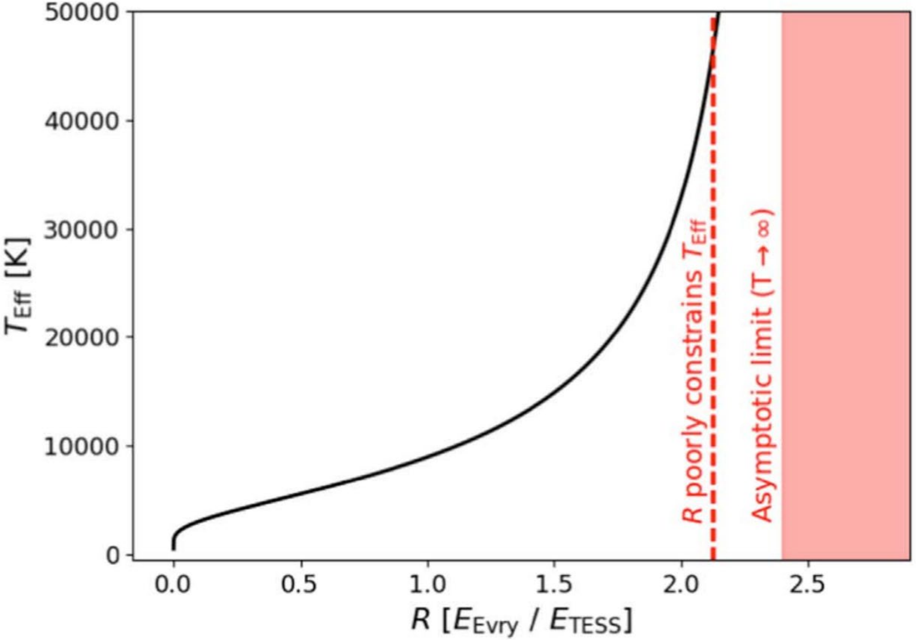
Assuming $A_{\rm fl}$ does not vary appreciably between the g' and T bandpasses and the areas cancel, dividing $F_{g'}$ by $F_{\rm T}$ results in the following equation:

$$\frac{F_{g'}}{F_{\rm T}} = \frac{X_{g'} B_{g'}(T_{\rm fl})}{X_{\rm T} B_{\rm T}(T_{\rm fl})} \approx \frac{B_{g'}(T_{\rm fl})}{B_{\rm T}(T_{\rm fl})}. \qquad (2)$$

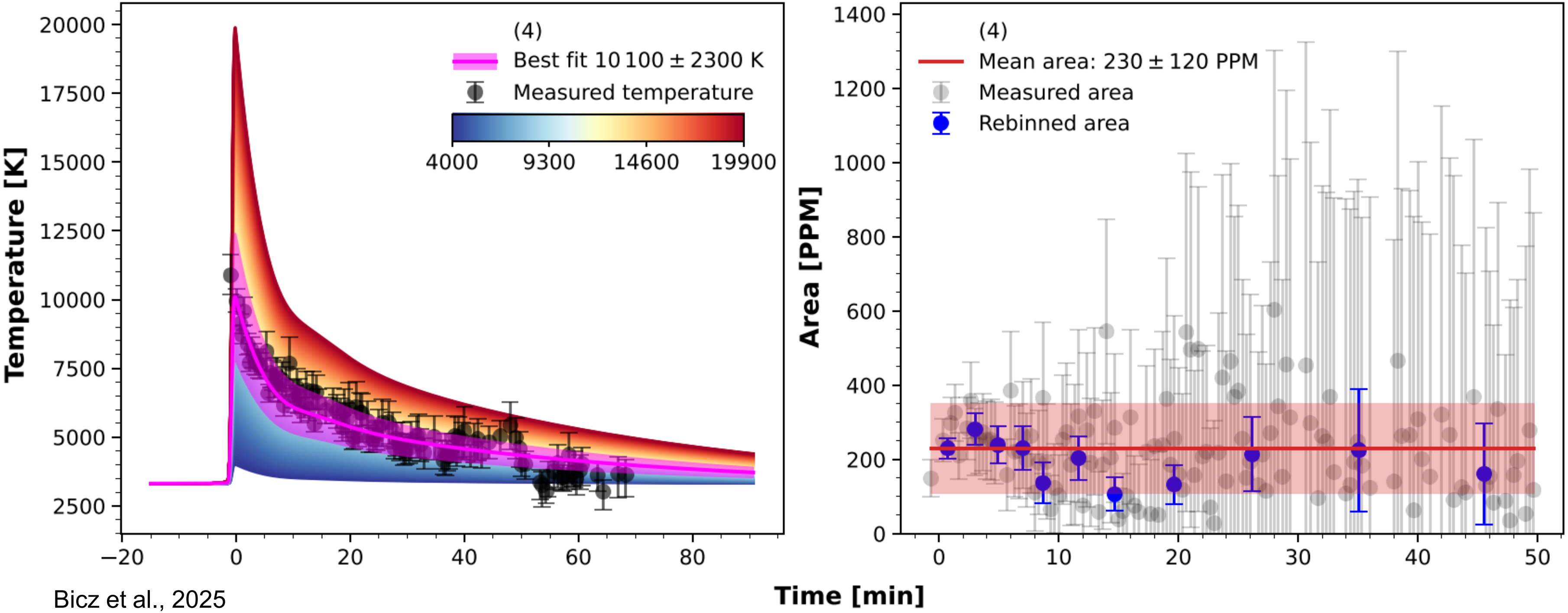


$$I_\nu = I_{\rm bg} e^{-\tau_\nu} + S_\nu(1 - e^{-\tau_\nu})$$

Heinzel, 2024



Howard et al., 2020



Bicz et al., 2025

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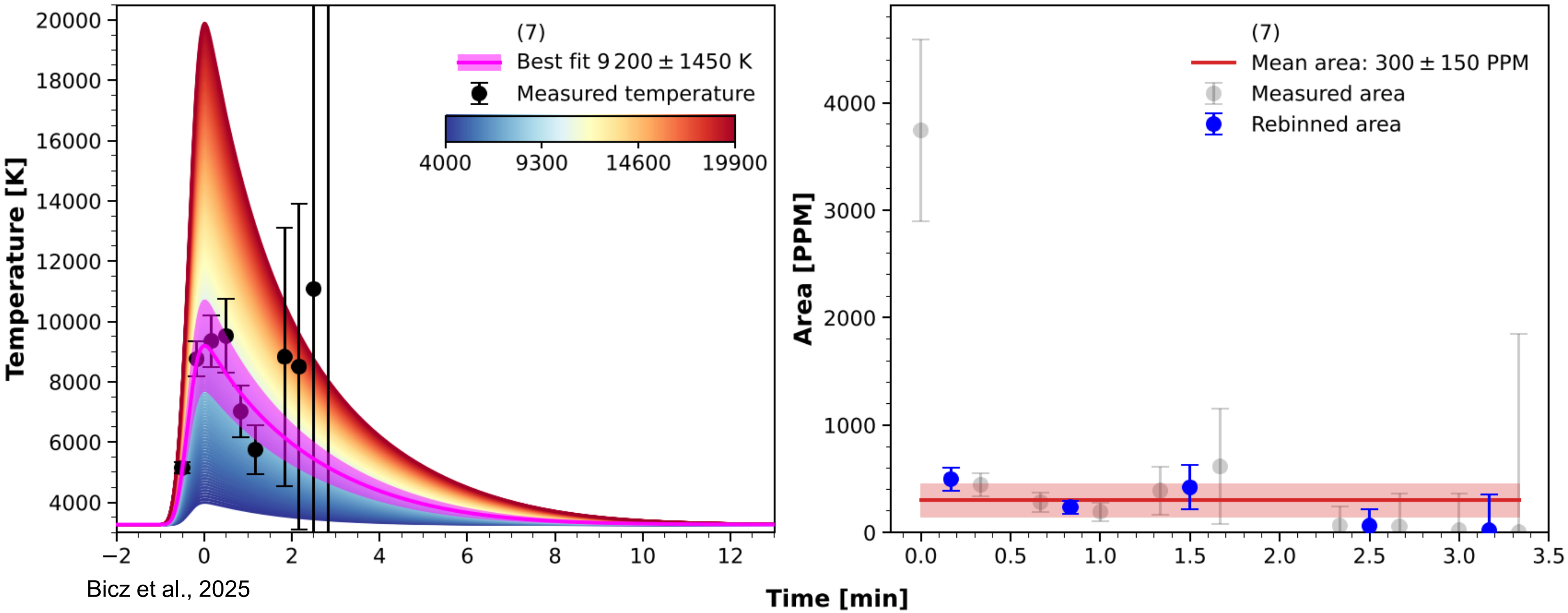

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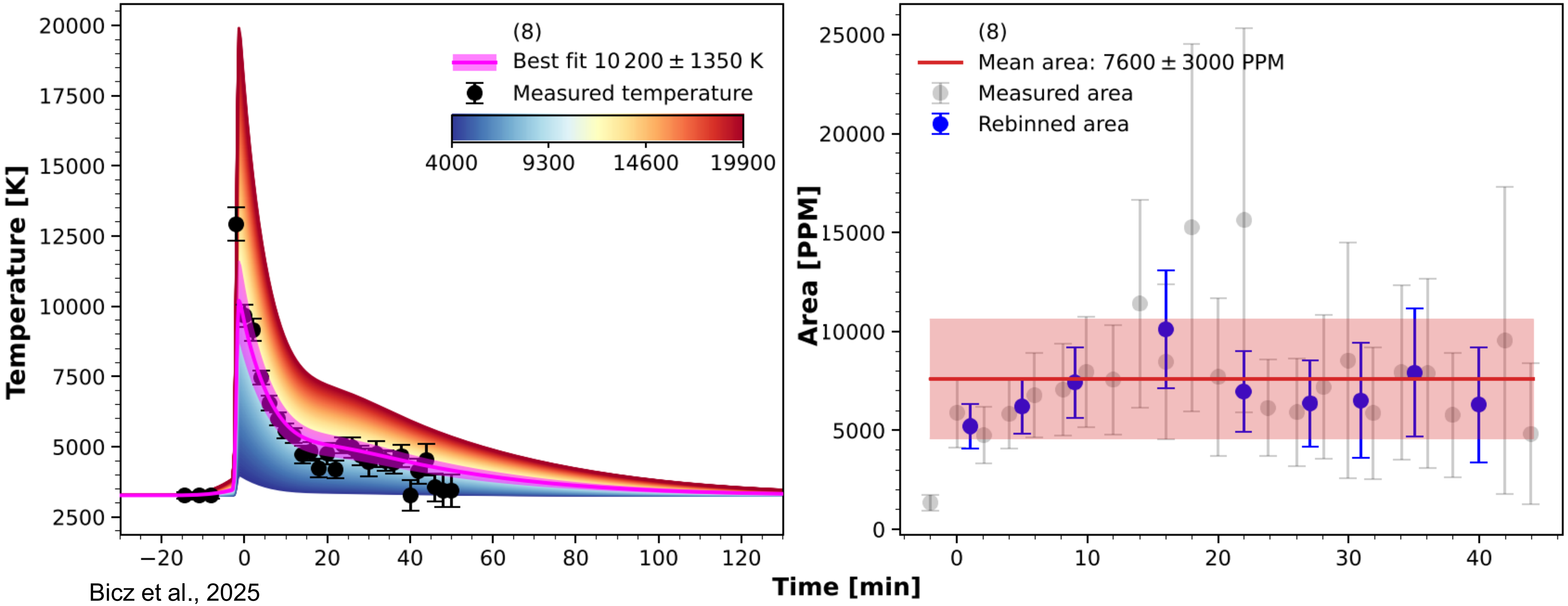

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Constant flare temperature T_{flare} = 10 000 K

$$C_{\rm flare} = \frac{F_{\rm flare}}{F_{\rm star}}, \quad (14)$$

where $F_{\rm star}$ is the observed luminosity of the star and $F_{\rm flare}$ is the observed luminosity of the flare:

$$F_{\rm star} = \pi R_{\rm star}^2 \int S_{\rm TESS} B_\lambda(T_{\rm eff}) d\lambda, \quad (15)$$

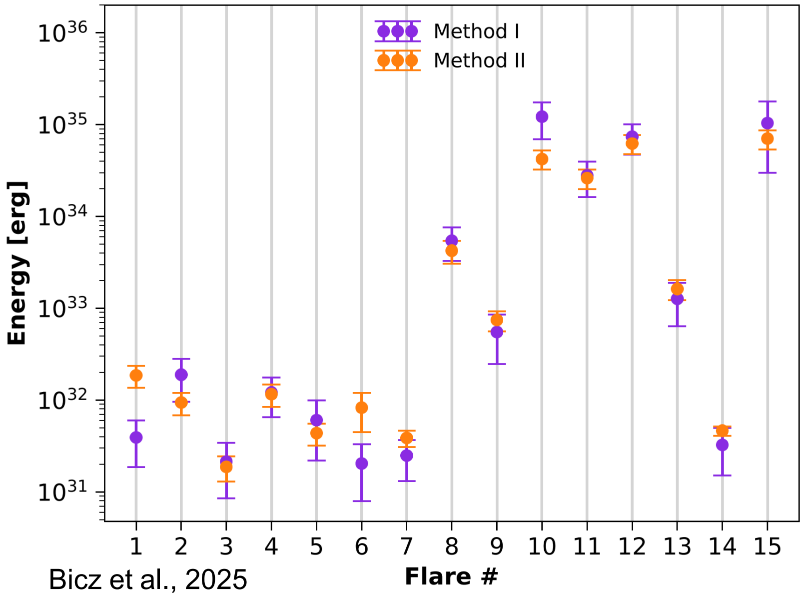
$$F_{\rm flare} = C_{\rm flare} \int S_{\rm TESS} B_\lambda(T_{\rm flare}) d\lambda, \quad (16)$$

$$A_{\rm flare} = C_{\rm flare}\, \pi R_{\rm star}^2 \frac{\int S_{\rm TESS} B_\lambda(T_{\rm eff}) d\lambda}{\int S_{\rm TESS} B_\lambda(T_{\rm flare}) d\lambda}, \quad (17)$$

where $S_{\rm TESS}$ is the TESS response function, and B_λ is the Planck function. The bolometric flare energy can then be calculated from:

$$E_{\rm flare} = \sigma_{SB} T_{\rm flare}^4 \int_{flare} A_{\rm flare}(t) dt. \quad (18)$$

$$E_{\rm flare} = \sum_{i=0}^{n-1} \left(A_{{\rm flare},\,i}\, \Delta t_i\, \pi \int_0^{+\infty} B_\lambda(T_{{\rm flare},\,i})\, d\lambda \right),$$



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Solar Optical Telescope (SOT)

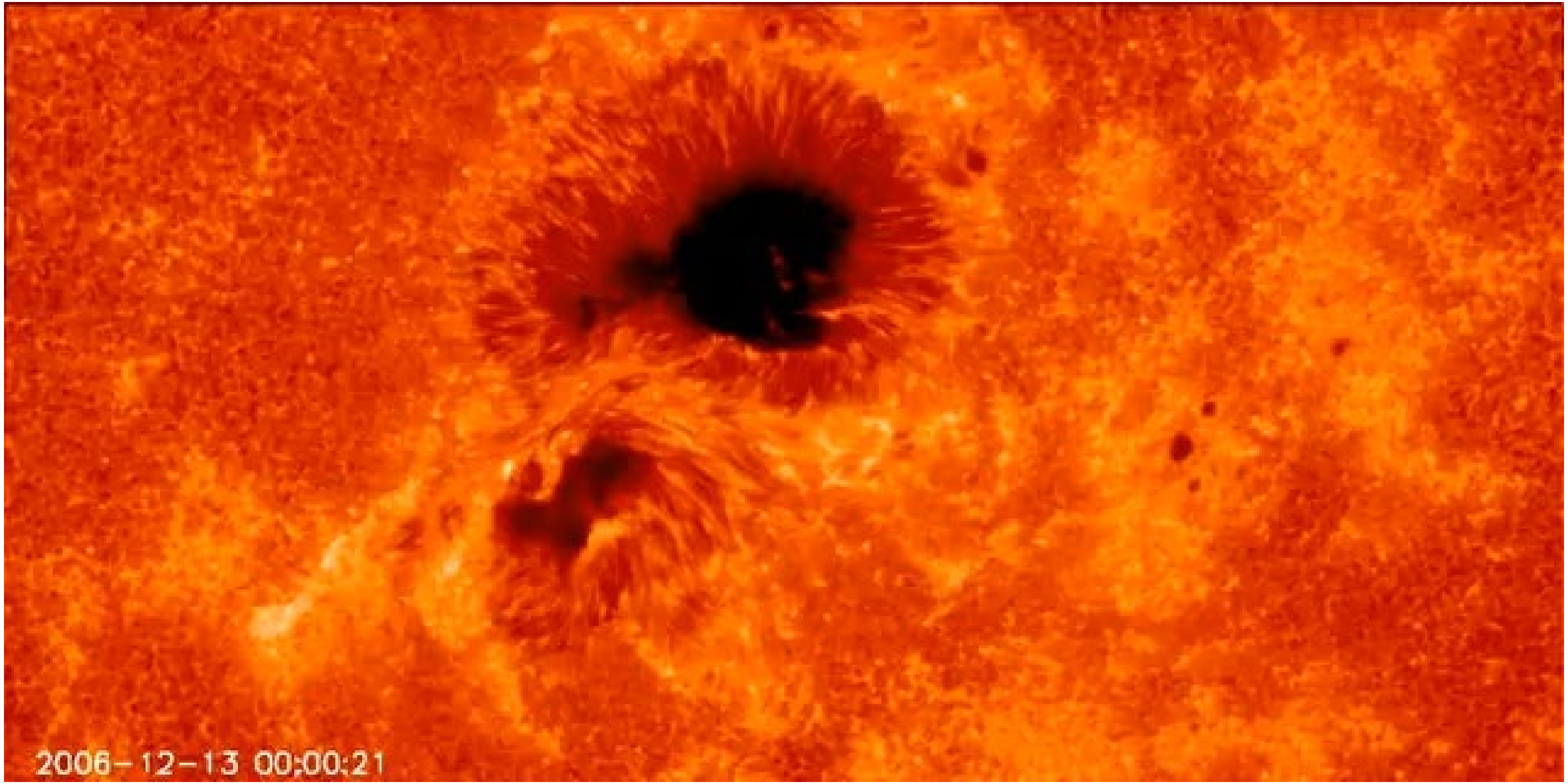


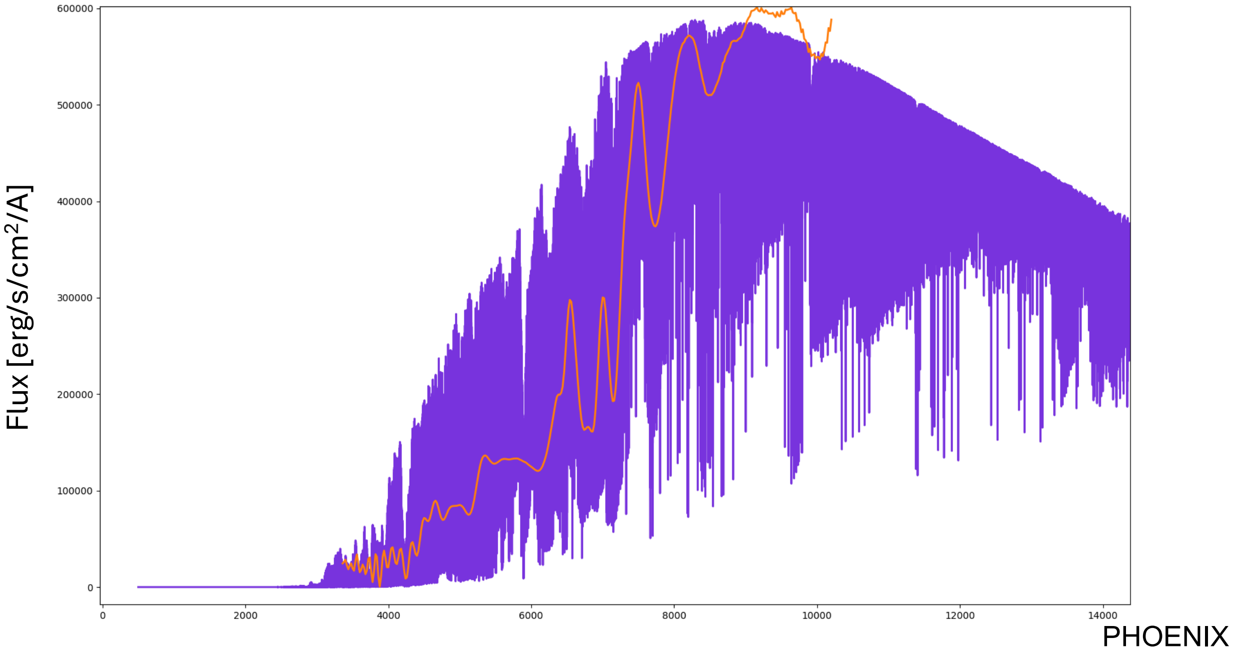
Table 3. Peak temperatures, mean areas, and F-test results for constancy of flare area over time.

Flare #	$T_{\rm flare}$ [K]	$A_{\rm flare}$ [ppm]	Relative area change [%]	p value	Method I [erg]	Method II [erg]
1	5 700 ± 450	210 ± 120	17	0.15	$(3.9 \pm 2.1) \times 10^{31}$	$(1.9 \pm 0.5) \times 10^{32}$
2	13 900 ± 1 900	370 ± 180	33	0.13	$(1.9 \pm 0.9) \times 10^{32}$	$(9.4 \pm 2.6) \times 10^{31}$
3	6 400 ± 1 800	150 ± 90	43	0.49	$(2.1 \pm 1.3) \times 10^{31}$	$(1.9 \pm 0.6) \times 10^{31}$
4	10 100 ± 2 300	230 ± 120	10	0.64	$(1.2 \pm 0.6) \times 10^{32}$	$(1.2 \pm 0.3) \times 10^{32}$
5	11 100 ± 3 150	220 ± 140	61	0.24	$(6.1 \pm 3.9) \times 10^{31}$	$(4.4 \pm 1.2) \times 10^{31}$
6	17 500 ± 10 000	50 ± 30	33	0.57	$(2.0 \pm 1.3) \times 10^{31}$	$(8.3 \pm 3.8) \times 10^{31}$
7	9 200 ± 1 450	300 ± 150	51	0.45	$(2.5 \pm 1.2) \times 10^{31}$	$(3.9 \pm 0.8) \times 10^{31}$
8	10 200 ± 1 350	7 600 ± 3 000	13	0.38	$(5.4 \pm 2.2) \times 10^{33}$	$(4.2 \pm 1.2) \times 10^{33}$
9	7 000 ± 3 100	440 ± 240	18	0.63	$(5.5 \pm 3.0) \times 10^{32}$	$(7.5 \pm 1.9) \times 10^{32}$
10	31 500 ± 10 050	3 200 ± 1 200	14	0.46	$(1.2 \pm 0.5) \times 10^{35}$	$(4.2 \pm 1.0) \times 10^{34}$
11	18 200 ± 2 850	2 900 ± 1 200	41	0.07	$(2.8 \pm 1.2) \times 10^{34}$	$(2.6 \pm 0.6) \times 10^{34}$
12	15 400 ± 3 550	4 700 ± 1 400	19	0.11	$(7.4 \pm 2.7) \times 10^{34}$	$(6.2 \pm 1.5) \times 10^{34}$
13	12 600 ± 7 050	410 ± 160	27	0.14	$(1.3 \pm 0.6) \times 10^{33}$	$(1.6 \pm 0.4) \times 10^{33}$
14	7 500 ± 2 350	380 ± 200	39	0.21	$(3.3 \pm 1.7) \times 10^{31}$	$(4.6 \pm 0.6) \times 10^{31}$
15	12 500 ± 2 650	2 200 ± 1 500	10	0.51	$(1.0 \pm 0.7) \times 10^{35}$	$(7.0 \pm 1.7) \times 10^{34}$

Notes. The p value of the F-statistic shows whether the slope of the regression is statistically significant, meaning whether the flare area changes over time. The relative area change below Flare 7 separates our observed flares from the data presented in Howard et al. (2020).

Bicz et al., 2025

Is it possible to correlate the star's effective temperature with the flare's peak temperature and amplitude?



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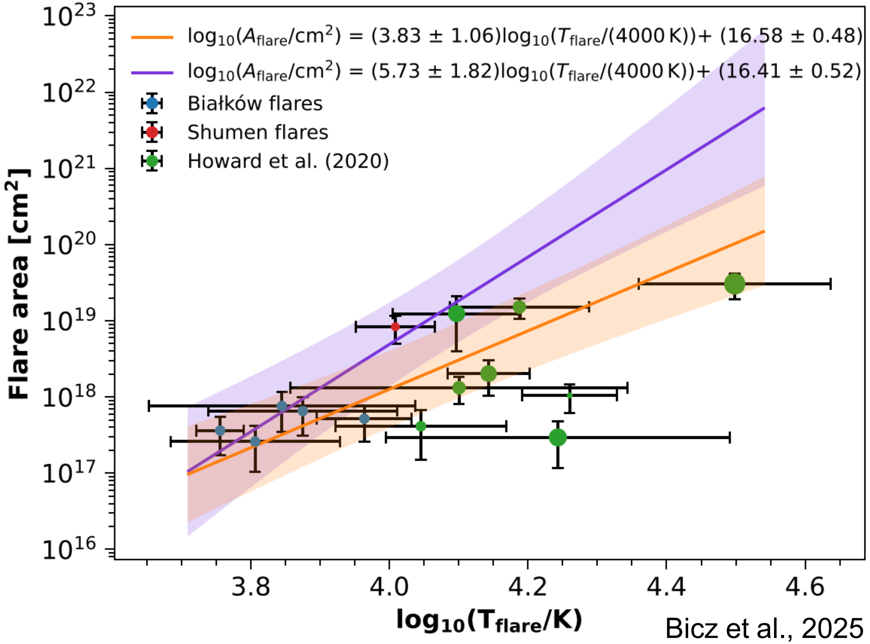
Is it possible to correlate the star's effective temperature with the flare's peak temperature and amplitude?



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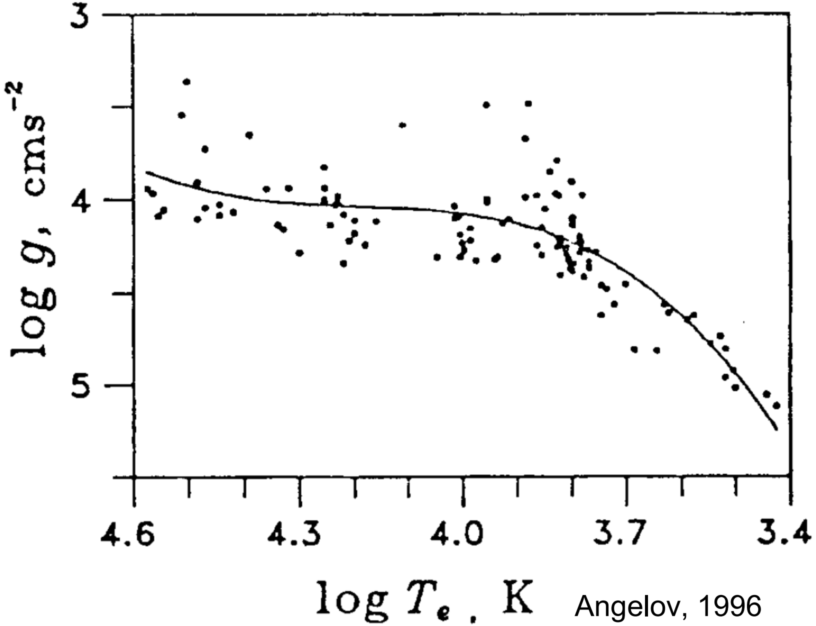

Angelov, 1996

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Cassisi & Salaris (2019), for the stars that have effective temperatures in the range 2700 K $\leq T_{\rm eff} \leq$ 3200 K

$$R_{\rm star}(T_{\rm eff})\,[{\rm R}_\odot] = (1.644\,(T_{\rm eff}/5777) - 0.677) \pm 0.1. \tag{10}$$

Similarly, the next equation presents the corrected relation from Boyajian et al. (2017), for stars that have effective temperatures in the range 3200 K $< T_{\rm eff} \leq$ 5500 K

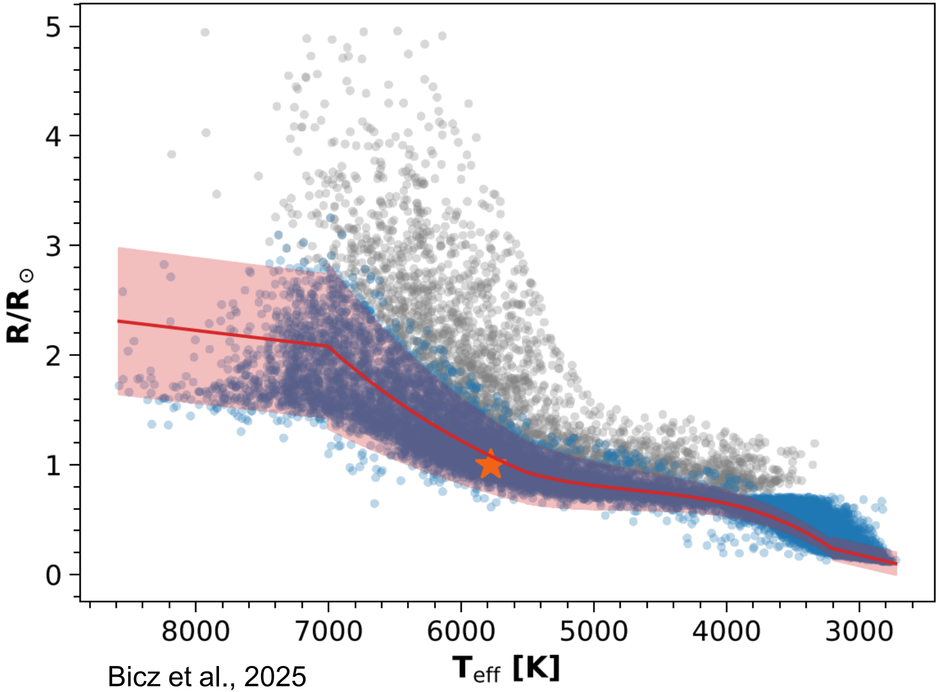
$$\begin{aligned} R_{\rm star}(T_{\rm eff})\,[{\rm R}_\odot] = {} & (-10.933 \pm 0.014) + \\ & + (7.188 \pm 0.009) \times 10^{-3} T_{\rm eff} - \\ & + (1.510 \pm 0.002) \times 10^{-6} T_{\rm eff}^2 + \\ & + (1.076 \pm 0.016) \times 10^{-10} T_{\rm eff}^3. \end{aligned} \tag{11}$$

The following equations represent our fitted models for main-sequence stars, each applying to different temperature ranges. For stars with effective temperatures in the range 5500 K $<$ $T_{\rm eff} \leq$ 7000 K, the stellar radius is given by:

$$\begin{aligned} R_{\rm star}(T_{\rm eff})\,[{\rm R}_\odot] = {} & 10^{(0.000220\pm0.000021)\cdot T_{\rm eff}-(1.209\pm0.178)} - \\ & + (0.080 \pm 0.002). \end{aligned} \tag{12}$$

For stars with effective temperatures in the range 7000 K $<$ $T_{\rm eff} \leq$ 8600 K, the stellar radius follows the relation:

$$R_{\rm star}(T_{\rm eff})\,[{\rm R}_\odot] = \left((14.48 \pm 2.638) \times 10^{-5}\right) \cdot T_{\rm eff} + (1.067 \pm 0.625).$$



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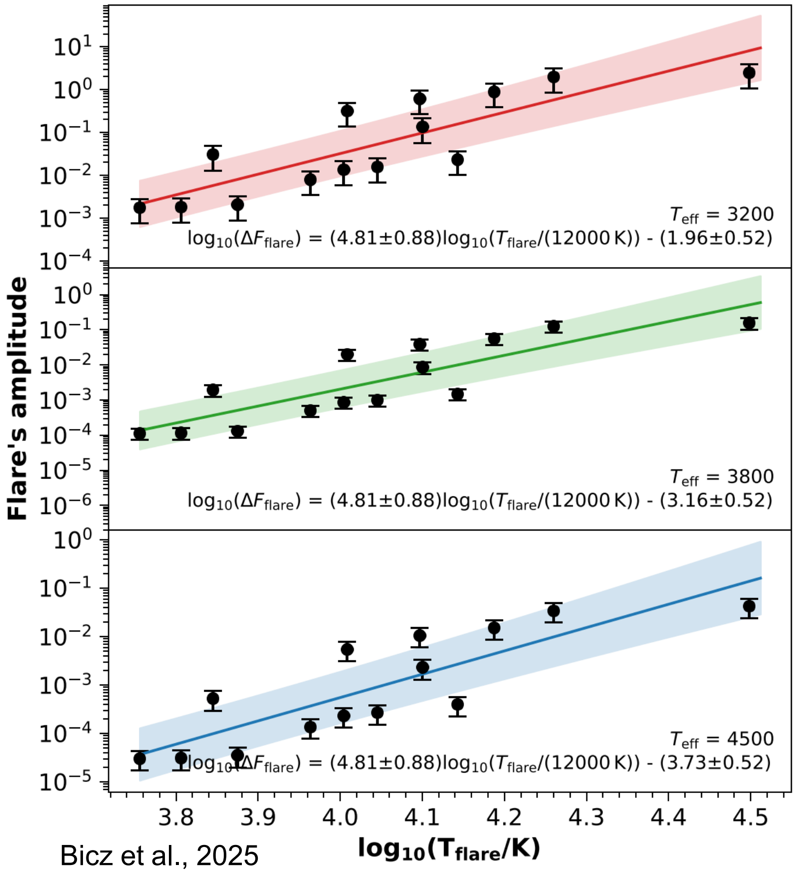

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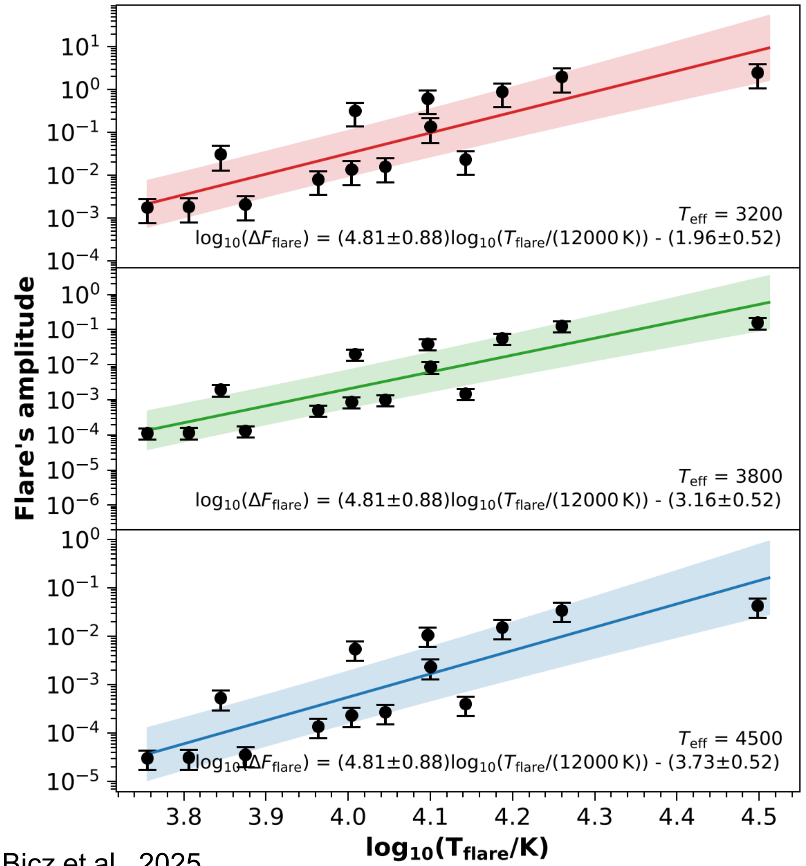
$$L_{\rm flare} = A_{\rm flare} \int_{\lambda_1}^{\lambda_2} B_\lambda(T_{\rm flare}) S_{\rm TESS}\, d\lambda,$$

+

$$L_{\rm star} = \pi R_{\rm star}^2 \int_{\lambda_1}^{\lambda_2} \mathcal{F}_\lambda S_{\rm TESS}\, d\lambda,$$

$$\log_{10}(\Delta F_{\rm flare}) = a \cdot \log_{10}(T_{\rm flare}) + b,$$



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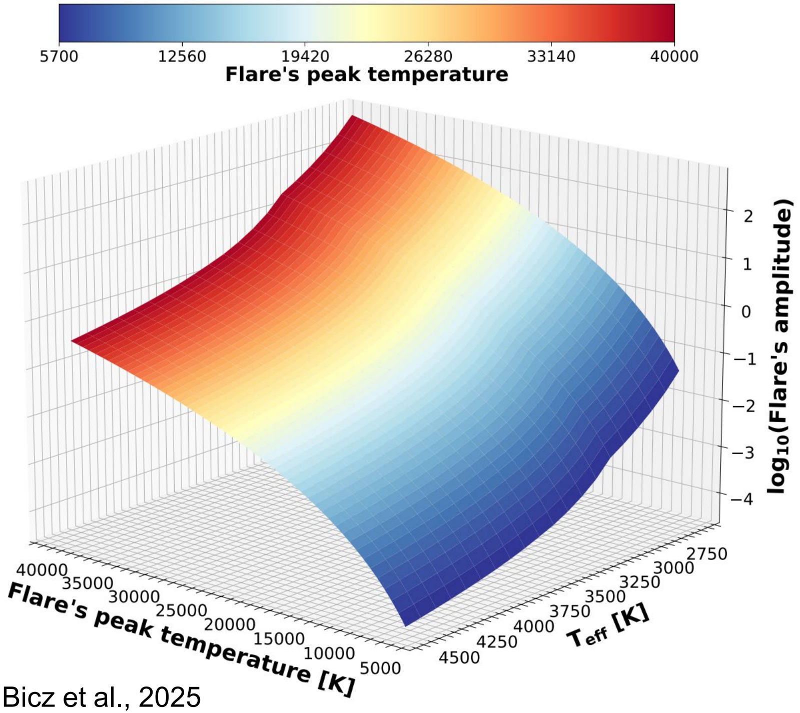

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It is now possible to estimate the temperature of the stellar flare using single-color photometry!

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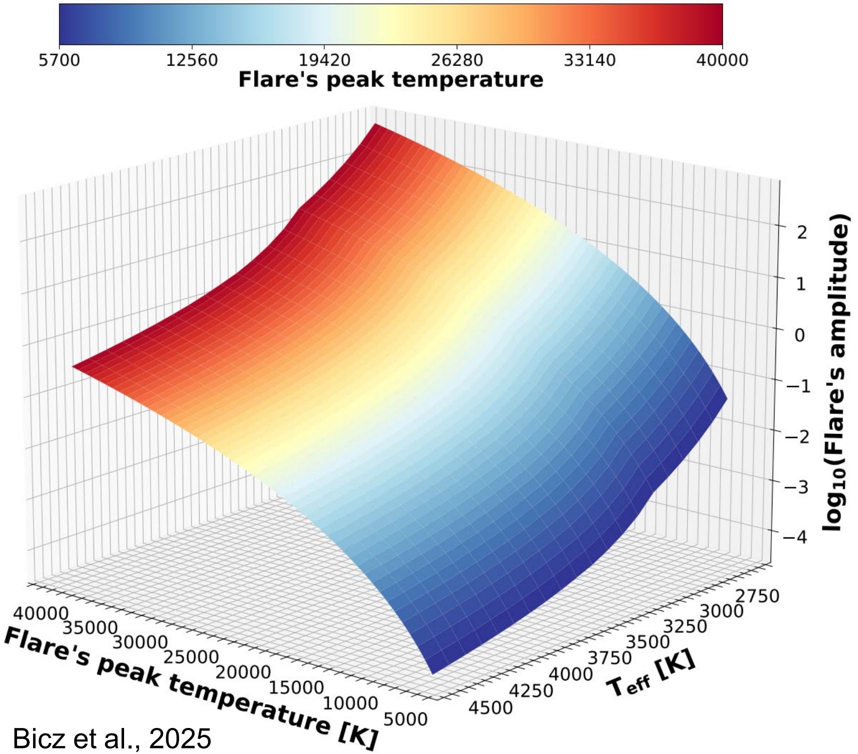

Bicz et al., 2025

Want to use our grid? Just scan me!

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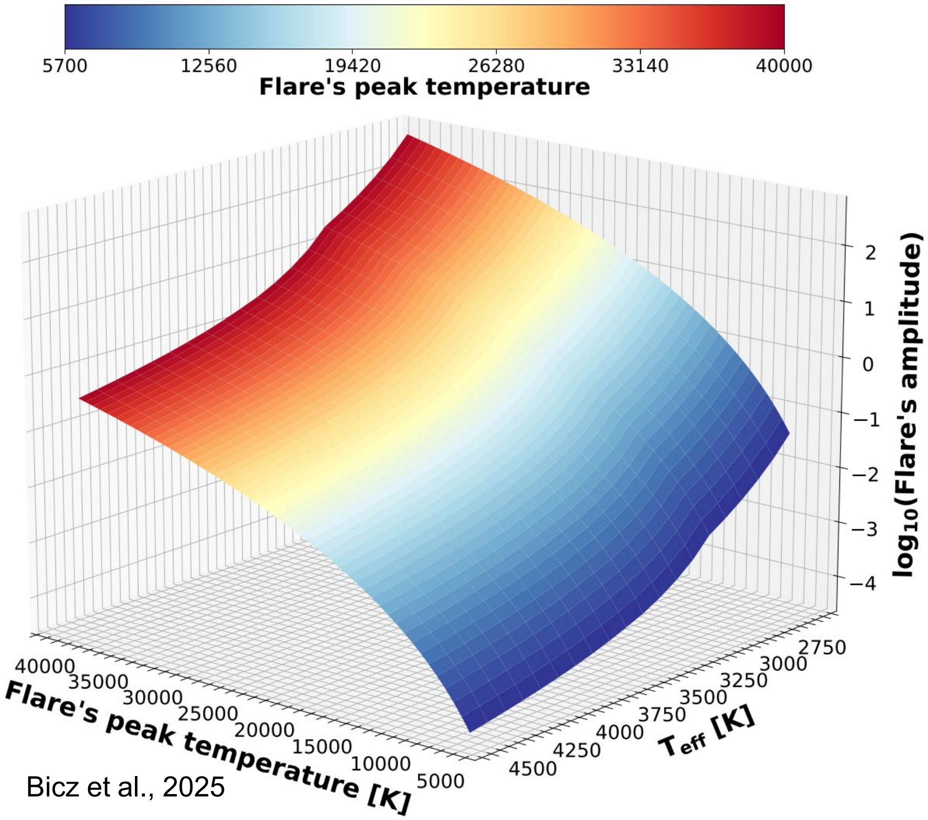
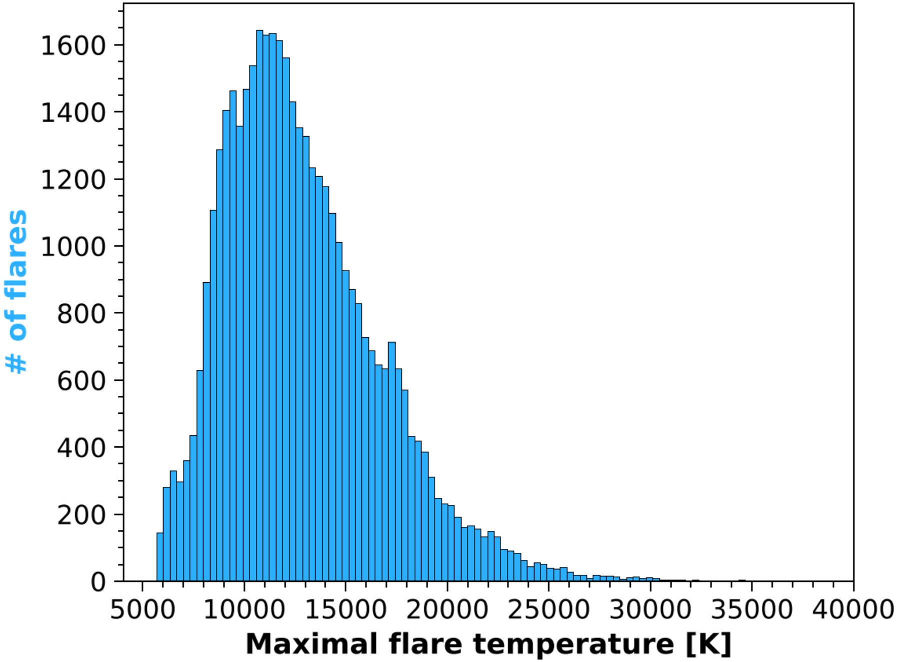


Bicz et al., 2025



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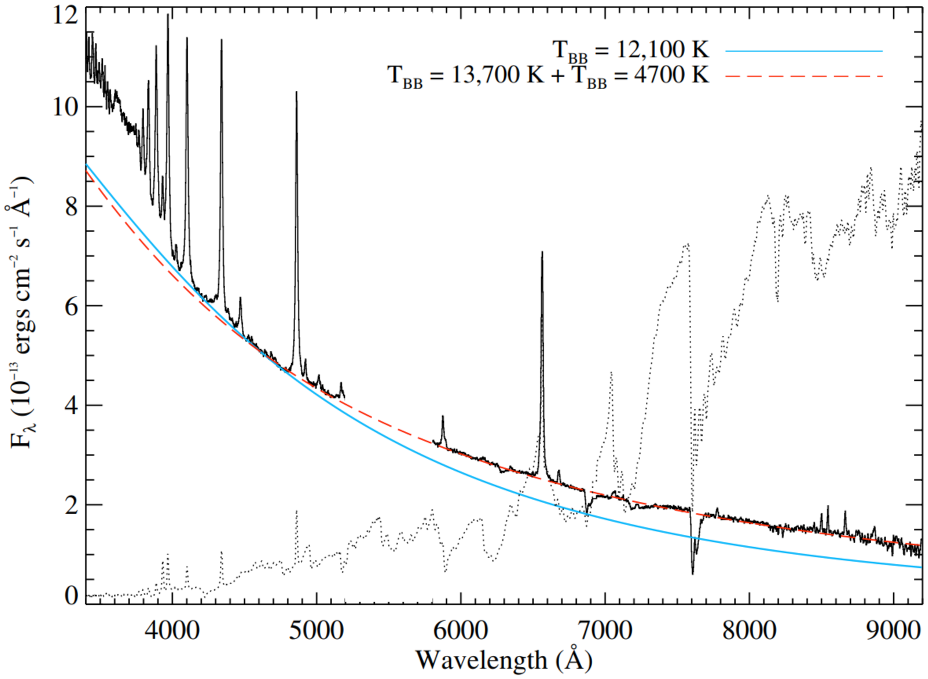

Figure 32. The peak flare-only spectrum of IF3 (S#31, black) from λ = 3400–9200 Å. The blackbody fit to the blue-optical zone (BW1–BW6; Table 4) is shown in light blue. A fit using the sum of two blackbody curves (BW3–BW6, RW1–RW3) is shown as a red dashed line. The quiescent spectrum is shown as a dotted line.

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 207:15 (57pp), 2013 July
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TIME-RESOLVED PROPERTIES AND GLOBAL TRENDS IN dMe FLARES FROM SIMULTANEOUS PHOTOMETRY AND SPECTRA*

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ABSTRACT

We present a homogeneous analysis of line and continuum emission from simultaneous high-cadence spectra and photometry covering near-ultraviolet and optical wavelengths for 20 M dwarf flares. These data were obtained to study the white-light continuum components at bluer and redder wavelengths than the Balmer jump. Our goals were to break the degeneracy between emission mechanisms that have been fit to broadband colors of flares and to provide constraints for radiative-hydrodynamic (RHD) flare models that seek to reproduce the white-light flare emission. The main results from the analysis are the following: (1) the detection of Balmer continuum (in emission) that is present during all flares and with a wide range of relative contributions to the continuum flux at bluer wavelengths than the Balmer jump; (2) a blue continuum at flare maximum that is linearly decreasing with wavelength from λ = 4000–4800 Å, indicative of hot, blackbody emission with typical temperatures of $T_{BB} \sim$ 9000–14,000 K; (3) a redder continuum apparent at wavelengths longer than Hβ (λ $\gtrsim$ 4900 Å) which becomes relatively more important to the energy budget during the late gradual phase. The hot blackbody component and redder continuum component have been detected in previous studies of flares. However, we have found that although the hot blackbody emission component is relatively well-represented by a featureless, single-temperature Planck function, this component includes absorption features and has a continuum shape strikingly similar to the spectrum of an A-type star as directly observed in our flare spectra. New model constraints are presented for the time evolution among the hydrogen Balmer lines and between Ca II K and the blackbody continuum emission. We calculate Balmer jump flux ratios and compare to the solar-type flare heating predictions from RHD models. The model ratios are too large and the blue-optical (λ = 4000–4800 Å) slopes are too red in both the impulsive and gradual decay phases of all 20 flares. This discrepancy implies that further work is needed to understand the heating at high column mass during dMe flares.

Key words: stars: atmospheres – stars: flare

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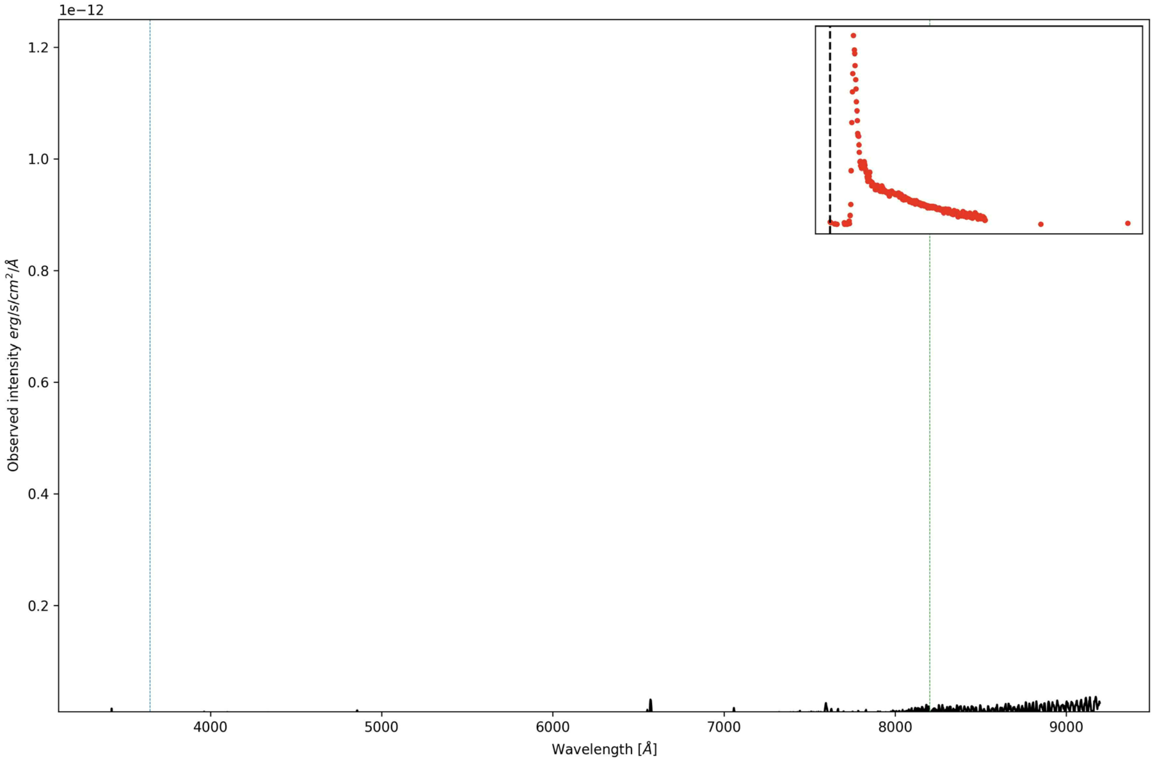

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Thank you for your attention!

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Bezovec
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