Simultaneous optical and mid-infrared observations of stellar flares: the overlap of TESS, Kepler and K2 with WISE

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Abstract

Space photometry has recorded hundreds of thousands of stellar flares in a single visible band, while at 3–5 μm simultaneous measurements have been lacking. The WISE/NEOWISE survey, with its 7.7-s exposures at 3.4 and 4.6 μm repeated every 95 min for a day or two twice a year during 2014–2024, is the only archive that can supply them for thousands of stars. We examine where and how often such exposures coincide with the flares catalogued by TESS, Kepler and K2, by cross-matching five catalogues against the individual NEOWISE and AllWISE measurements. The pointing rules of the missions leave no common sky at intermediate ecliptic latitudes: coincidences are confined to the ecliptic poles, to the ecliptic itself during the few TESS sectors pointed along it, to two AllWISE passes over the Kepler field, and to one WISE pass per K2 campaign. We give the resulting statistics, the precautions that the cross-match requires (proper motions, the drift of the NEOWISE photometry), a first methodological upper limit on the flare-averaged infrared response, and examples of what the single exposures reveal: a candidate infrared response to a flare, eclipses and spots followed in the infrared, and spurious catalogue flares at eclipse edges.

Keywords: *stars: flare — stars: activity — infrared: stars — surveys — methods: observational*

1 Introduction

The systematic detection and study of flare stars, which began at the Byurakan and Tonantzintla observatories in the 1950s–70s (Ambartsumian, 1969; Ambartsumyan et al., 1970; Haro, 1957), has continued in the present era thanks to the Kepler and TESS missions, with a cadence of minutes and a precision of a fraction of a percent, and the catalogues built from these light curves contain hundreds of thousands of events (Feinstein et al., 2024; Ilin et al., 2021; Seli et al., 2025; Yang & Liu, 2019; Yudovich et al., 2025).

What the catalogues do not contain is colour: both missions observe in a single wide visible band, so the temperature of the flaring plasma and the way its energy is redistributed between the continuum and the chromospheric lines cannot be read from them. Ground-based work has shown that the flare continuum is close to a $\sim 10^4$ K black body (Kowalski et al., 2013) with a weak near-infrared response, below 5–8 mmag in JHK_s (Tofflemire et al., 2012). Beyond 3 μm there has been nothing: the mid-infrared is where a hot continuum is faintest against the photosphere of a cool star, but it is also where any reprocessing of the flare energy by circumstellar dust, or any change of the spotted photosphere accompanying the flare, would show up.

A systematic survey at these wavelengths exists, although it was not built for flares. WISE (Wright et al., 2010) and its continuation, NEOWISE (Mainzer et al., 2014), imaged the whole sky in the W1 (3.4 μm) and W2 (4.6 μm) bands from the end of 2013 to mid-2024, with every point being visited twice a year for one to several days, and with an exposure every 95 min; the single-exposure photometry is public, with a typical error of 0.02 mag for a star of W1 $\approx$ 11. The question we address is simple to pose and not trivial to answer: for which flares of the existing optical catalogues does a WISE exposure fall within hours of the peak, and what can such exposures tell us? This paper gives the answer for the geometry and the statistics and summarises the first results of the cross-match; the method is described in detail in a companion paper (Akopian et al., 2026, hereafter Paper I).

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2 Material

Five flare catalogues were used. Three of them come from the uniform reprocessing of 2-min TESS light curves with the TOFFEE algorithm (Pratt et al., 2026): members of 26 young groups and clusters (Feinstein et al., 2024), the 234 most active F–M stars of Yudovich et al. (2025), and the all-sky sample of 2-min targets, dominated by M dwarfs within 200 pc (Seli et al., 2025). To these, we added the Kepler flares of Yang & Liu (2019) for the 1742 stars of the Kepler field with multi-epoch AllWISE photometry, and the K2 flares of open-cluster members from Ilin et al. (2021) in Campaigns 4 and 5 (Pleiades, Hyades, Praesepe), which fall within the NEOWISE years. From the TESS catalogues we kept primary events with at least five points and an amplitude of at least five times the scatter; for Kepler and K2, whose catalogues list no peak time, the peak was located on the light curve between the catalogued start and end. After this selection, the material comprises 144 000 TESS flares of 14 400 stars, 79 000 Kepler flares, and 2500 K2 flares.

For every star, all individual detections within $3''$ of its position were taken from the NEOWISE-R Single Exposure Source Table at IRSA, along with their times, magnitudes, errors, and quality indicators; for the Kepler field, the AllWISE Multiepoch Photometry table plays the same role. The table for the TESS stars holds six million measurements of 14 400 stars, a median of 320 per star over eleven years. Two technical points matter. First, a fixed $3''$ cone loses a star with proper motion above $0.12''$ yr^{-1} before the end of the survey, and above $0.2''$ yr^{-1} almost entirely; a fifth of the Seli et al. (2025) sample moves that fast, and these are precisely the closest and infrared-brightest M dwarfs. We therefore search around the position propagated to 2019.0 with a radius enlarged by the expected displacement and keep only the detections within $3''$ of the star's position at the time of each frame; this restored the measurement series of 700 stars that had none and completed the truncated series of 1600 more. Second, the NEOWISE single-exposure photometry is not stationary: relative to the median over the whole mission, the yearly median of the quiescent exposures of the same stars moves from +8 mmag in 2014 to −6 mmag in 2020–2023 in W2 (from +2 to −1 mmag in W1), mostly as a step in 2017–2019, and more strongly for fainter stars. The drift, known from the data releases (Cutri et al., 2015), is coherent over the sky, harmless for a single exposure, and decisive when hundreds of flares are averaged.

3 How a flare is compared with the infrared exposures

The procedure is the same for all catalogues (Paper I). For each star and band a quiescent level is defined as the median of the clean exposures lying more than 0.85 d before or 2.1 d after any catalogued flare, with a robust scatter σ from the median absolute deviation and a floor at the median catalogue error; at least 15 such exposures are required. The deviation of every exposure from this level, taken positive for a brightening, is expressed in millimagnitudes and in units of σ (z). Around every flare two intervals are examined: a narrow window of ±0.2 d, holding typically two to four clean exposures, whose mean deviation is used for averaging over many flares; and a search interval from −0.75 d before to +2 d after the peak, within which the largest deviations before and after the peak and the times of the nearest exposures are recorded, and in which an exposure may fall on the flare itself. The asymmetry allows for a lagging response; the pre-flare part monitors the star. A flare counts as "simultaneous" if the search interval contains at least one clean exposure. For every observing series containing such a flare the program draws a combined figure (the optical light curve, the W1, W2 and W2−W1 deviations, and the deviations folded on the flare peak); these were inspected for all 1180 stars concerned and are the source of the by-products of Section 5.

4 Where the two surveys meet

The time spans of the surveys overlap for ten years, but their pointing rules nearly exclude each other (Fig. 1). TESS stares for 27 d at a strip of sky opposite the Sun; the WISE scan circle stands at a solar elongation of about 90° (82–98° in practice). A star at intermediate ecliptic latitudes is therefore observed by TESS a quarter of a year away from the WISE passes, whatever the sector. The two footprints share sky only at the ecliptic poles — crossed by the WISE circle on every orbit and kept in view by TESS Camera 4 in every sector of the corresponding hemisphere — and, briefly, near the ecliptic itself, when TESS departed from its anti-solar pointing in Sectors 42–46 (2021–2022): during such a sector the Sun advances by 27° and the WISE circle sweeps across the edge of the field. This is how the Pleiades, sitting at the edge of

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Camera 4 in Sector 42, came under the WISE strip on 2021 August 20–25, and how about 180 field stars of the Seli et al. (2025) and Feinstein et al. (2024) catalogues received exposures in Sectors 43–46. The Kepler field is fixed at ecliptic latitude ≈ 65°, outside the polar overlap, so WISE crossed it twice a year; only the two crossings of 2010 (April–May and October–November) are in the AllWISE multi-epoch data. The K2 fields lie on the ecliptic, and an 80-day campaign is long enough for the WISE circle to cross each of them once — making K2, rather than TESS, the natural optical partner of NEOWISE.

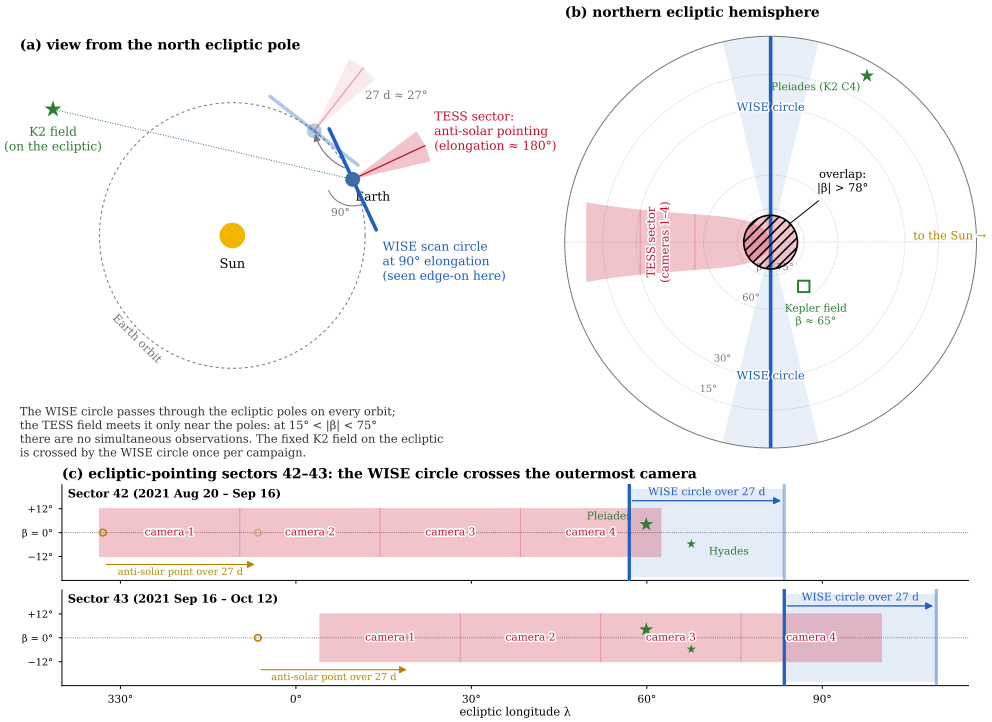


Figure 1: Why TESS and WISE rarely look at the same star. (a) The ecliptic plane seen from the north: the TESS field (red) points away from the Sun, the WISE scan plane (blue) stands at quadrature, and a K2 field (green star) sits on the ecliptic where the WISE plane sweeps across it once per campaign. (b) The northern ecliptic hemisphere in polar projection: the TESS sector with its four cameras, the WISE circle and the band it covers in 27 d, their overlap (hatched) within ≈ 12° of the pole, the Kepler field at $\beta \approx 65°$ and the Pleiades at $\beta \approx 4°$. (c) The ecliptic-pointed Sectors 42 and 43 drawn from the actual camera centres; the WISE meridian at the start of each sector and its displacement over 27 d cross the Pleiades (Sector 42) and Camera 4 east of them (Sector 43).

The cross-match turns this picture into numbers (Table 1, Fig. 2). In the three TESS catalogues not one flare between $|\beta| = 15°$ and 75° — nine thousand stars, a hundred thousand flares — has a WISE exposure in its search interval. Within 15° of the poles, 38–73% of the flaring stars have at least one such flare; within 15° of the ecliptic, 5–7% do, all of them from the ecliptic-pointed Sectors 42–46 or from K2 Campaign 4. Over the whole sky the fraction of simultaneous flares is 1–3% for the TESS samples, 2.4% for K2 and 0.8% for Kepler, whose two short AllWISE series cover a few days of a four-year mission. In absolute terms the yield is not small: about 3000 flares in the search interval, 1750 within six hours of the peak and 740 within one hour. Two thirds of them belong to the Seli et al. (2025) sample, the largest and the one whose polar targets TESS observed in many consecutive sectors.

For the clusters the dates were decisive. The WISE pass over the Pleiades and the Hyades fell in the first eight days of K2 Campaign 4 (February 2015), with some thirty clean exposures per star: 55 flares of 51 Pleiades stars are simultaneous, 13 of them within an hour of the peak. The pass over Praesepe ended on 2015 April 26, one day before Campaign 5 began, and Praesepe has no simultaneous flare at all. Six and a half years later Sector 42 gave the Pleiades a second epoch. The Pleiades are thus the only cluster with two epochs of joint optical and mid-infrared flare coverage, about a hundred flares of ninety coeval stars, and this is where the individual events are now being sought.

Table 1: Outcome of the cross-match. A flare is "simultaneous" if a clean WISE exposure falls between −0.75 and +2 d of its peak.

Catalogue	Flares / stars	Simultaneous: flares / stars	Within 1 h / 6 h	Where
Feinstein et al. (2024), TESS	11 744 / 1887	156 / 91	35 / 97	poles; Sector 43
Yudovich et al. (2025), TESS	9 754 / 225	264 / 48	58 / 164	poles
Seli et al. (2025), TESS	122 958 / 12 245	1936 / 707	471 / 1178	poles; Sectors 42–46
Yang & Liu (2019), Kepler × AllWISE	79 287 / 1742	599 / 403	165 / 280	two series, 2010
Ilin et al. (2021), K2	2 544 / 841	60 / 56	13 / 26	Pleiades, Hyades (C4); Praesepe none

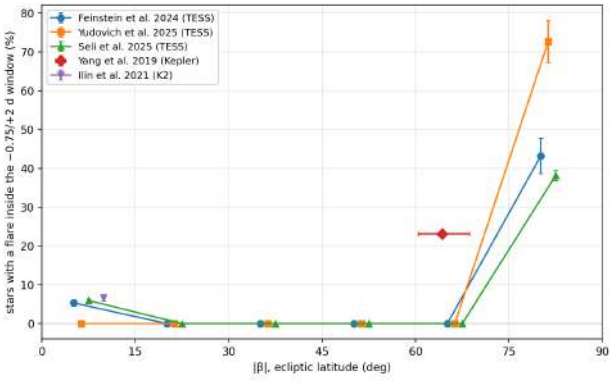


Figure 2: Fraction of flaring stars with at least one simultaneous flare, as a function of absolute ecliptic latitude, for the five catalogues; the Kepler field is one point with the latitude spread of the field. The empty band between 15° and 75° is the geometry of Fig. 1, not a lack of data.

5 What a first pass yields

A methodological upper limit. Averaging the ±0.2 d window means over the 796 flares of the Seli et al. (2025) sample that have a clean exposure in the window, pass the quality selection and belong to stars fainter than the saturation limit (W1 > 8), we find no response: the deviation from the expectation is 0.0 ± 0.6 mmag in W1, -0.8 ± 0.7 in W2 and -0.9 ± 0.7 in W2−W1, giving 95% upper limits of 0.96 and 1.13 mmag on a brightening in W1 and W2 and of 1.23 mmag on a reddening of W2−W1; for 129 Kepler flares with AllWISE exposures the W1 limit is 4.9 mmag. The expectation is not zero: all TESS flares date from 2018–2023, so that a quiescent level taken over the whole mission turns the drift of Section 2 into a spurious mean dimming of -2.0 ± 0.5 mmag in W1 and -6.0 ± 0.4 mmag in W2; the control windows must be drawn from the same observing series as the flare, and for Kepler the two AllWISE series, which straddle the end of the cryogenic phase and differ by 30 mmag in W2, must never be mixed. And the limit, robust as it is, constrains little of the physics: a typical flare of the sample has an equivalent duration of half a minute, a thousandth of the window, so that both its own infrared emission and any reprocessing by hot dust are diluted a thousandfold. A sub-millimagnitude null over 0.4 d bounds only responses lasting hours; the flare itself must be caught within minutes of the peak, and Section 4 says where that can happen.

By-products. At 95-min cadence over series of one to eight days, the single exposures follow eclipses and rotational or ellipsoidal modulation with periods from hours to a week. In the eclipsing binary TIC 233679640 (Fig. 3) the 40 exposures of a five-day series trace both the 27%-deep eclipses and the 30% wave between them, with a correlation of 0.97 in W1 and 0.96 in W2 between the TESS flux at the exposure times and the infrared brightening; a period search over the ten to twenty series of each of the 13 500 Seli et al. (2025) stars is thus a feasible by-product. The same figure shows eight of the nine catalogue "flares" of this series crowded on the ingress and egress of the two eclipses, where the detection algorithm took the steep branches for flares (the ninth, on the plateau between them, is a probable flare); left in a sample they would imitate an infrared "response" of either sign, since the star really changes brightness at those moments. The shape criterion (a decay at least 1.5 times longer than the rise, a rise shorter than an hour; Davenport et al. 2014) rejects half of them, and the classification of the star as eclipsing from the combined figure removes the rest; the infrared series thus act as an independent check of the optical flare catalogues.

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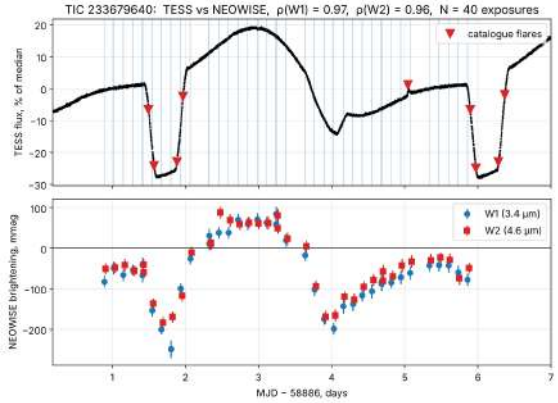


Figure 3: The eclipsing binary TIC 233679640 (catalogue of Seli et al. 2025): the TESS light curve of Sector 21 and the 40 NEOWISE exposures of one observing series. Top: the TESS flux in per cent of the median, the vertical lines marking the exposures and the triangles the catalogue "flares"; bottom: the brightening in W1 and W2 relative to the quiescent level of the star. ρ is the correlation of the TESS flux at the exposure times with the infrared brightening.

A candidate infrared response. Of the 740 flares with an exposure within an hour of the peak, the most telling are those where the exposure falls on the flare itself. TIC 275133493, an M dwarf of the Seli et al. (2025) sample near the ecliptic ($\beta \approx -8°$), observed in the ecliptic-pointed Sector 45, is such a case (Fig. 4). A flare of 2021 November 15 raised the TESS flux by 3.7 times the quiescent level (an amplitude of 370%) and lasted two and a half hours. The exposure 48 min after the peak, on the decay, when the TESS flux was 107% above quiescence, shows $+83 \pm 21$ mmag in W1 (4.2σ) and $+134 \pm 31$ mmag in W2 (4.3σ); the next one, 142 min after the peak at an optical excess of 36%, still shows $+32 \pm 19$ mmag in W1. The ratio of the optical to the W1 flare flux, 13 and 12 at the two moments, is what a 10^4 K continuum over an M-dwarf photosphere predicts (9–15); the noisier W2 series shows 2.5σ deviations before the flare as well. A single event at four sigma per band is a candidate rather than a detection; the K2 epoch of the Pleiades, however, has produced two flares with simultaneous W1 and W2 brightenings at 13.5σ and 6.3σ in W1, which are analysed in a separate paper.

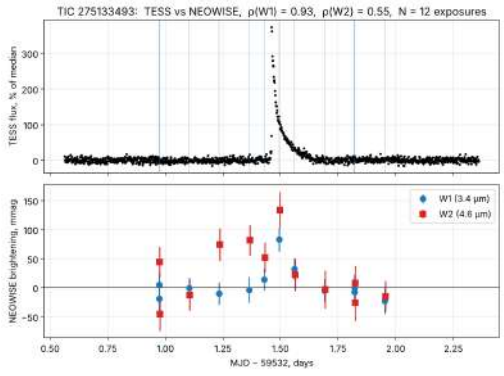


Figure 4: A candidate infrared response: TIC 275133493 (TESS Sector 45). Top: the TESS light curve in per cent of the median, the vertical lines marking the NEOWISE exposures; bottom: the brightening in W1 and W2 in these exposures relative to the quiescent level, with catalogue errors. ρ is the correlation of the TESS flux at the exposure times with the infrared brightening.

6 Conclusions

Simultaneous optical and mid-infrared observations of stellar flares are a matter of pointing, not of time overlap: for TESS and WISE they exist only within about 15° of the ecliptic poles and, during a handful of sectors, on the ecliptic, while K2 provided them in every campaign. The cross-match of five catalogues

with the WISE single exposures gives about 3000 flares with an exposure in the search interval, 740 of them within an hour of the peak, and about a hundred flares of Pleiades members observed jointly at two epochs. Recovering the nearest stars requires the proper motions to be carried through the eleven years of the survey, and averaging over many flares requires the drift of the NEOWISE photometry to be removed series by series; with these precautions, the flare-averaged response within ±0.2 d is below about 1 mmag, a limit that speaks to the method rather than the flares. NEOWISE also proves a serviceable monitor of eclipses and spots and an independent check of the flare catalogues. The physics of the flares at 3–5 μm will come from exposures that fall on a flare in progress, and those are concentrated where this paper says to look.

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