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Synthesizing Sun-as-a-star flare spectra from high-resolution solar observations

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ABSTRACT

Context. Spatially resolved observations of the Sun and the astronomical sample size of stellar bodies are the respective key strengths of solar and stellar observations. However, the large difference in object brightness between the Sun and other stars has led to distinctly different instrumentation and methodologies between the two fields.

Aims. We produced and analyzed synthetic full-disk spectra derived from 19 small area field-of-view optical observations of solar flares acquired by the Swedish 1-m Solar Telescope (SST) between 2011 and 2024. These were used to investigate what can and cannot be inferred about physical processes on the Sun from Sun-as-a-star observations.

Methods. The recently released Numerical Empirical Sun-as-a-Star Integrator (NESSI) code provides synthetic full-disk integrated spectral line emission based on smaller field-of-view input while accounting for center-to-limb variations and differential rotation. We used this code to generate pseudo-Sun-as-a-star spectra from the SST observations.

Results. We show that limited-area solar observations can be extrapolated to represent the full disk accurately in a manner close to what is achievable with Sun-as-a-star telescopes. Additionally, we identify nine spectral features, four of which are caused by instrumental effects. Most notably, we find a relation between the heliocentric angle of flares and the width of the excess emission left by them as well as a source of false positive coronal mass ejections-like signatures, and we defined an energy scaling law based on chromospheric line intensities that shows that the peak flare contrast roughly scales with the square root of the bolometric energy.

Conclusions. The presented method of creating pseudo-Sun-as-a-star observations from limited field-of-view solar observations allows for the accurate comparison of solar flare spectra with their stellar counterparts while allowing for the detection of signals at otherwise unachievable noise levels.

Key words. line: profiles – methods: data analysis – Sun: atmosphere – Sun: chromosphere – Sun: flares

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1. Introduction

Solar flares and the corresponding coronal mass ejections (CMEs) are the primary drivers of the most severe disruptions to the heliosphere (Cliver et al. 2022). When aimed at the Earth, they can cause widespread damage to electronics, blackouts, and disruptions in communications (e.g., Cole 2003; Miteva et al. 2023). The energies of these flares are typically between 10^{29} and 10^{33} erg (Fletcher et al. 2011), which is still two orders of magnitude lower than the most powerful stellar flares. These extreme events are believed to reach energies as high as 10^{35} or 10^{36} erg, depending on whether one adopts the assumption of blackbody radiation (Maehara et al. 2012) or hydrogen recombination continuum (Simões et al. 2024) for energy fitting. While solar flares leave only faint (Woods et al. 2006; Kretzschmar 2011) or at times no detectable (e.g., Pietrow et al. 2024a) signatures in the total solar irradiance, they can dramatically outshine their host stars when occurring on intrinsically dimmer M dwarfs (e.g., Zhan et al. 2019). They are also visible as dimmings in the corona and transition region (e.g., Hou et al. 2025; Veronig et al. 2025).

Although such extreme events have been observed on other stars for years (e.g., Pietras et al. 2022; Namizaki et al. 2023; Bruno et al. 2024), stellar flares have only recently attracted significant attention in the context of exoplanet research. In part because they are sources of noise and transit time variation (e.g., Davenport et al. 2019; Howard et al. 2023) but also since they are agents of change in planetary environments, where it is believed that flares and their ejecta can permanently alter planetary atmospheres and thus their habitability (e.g., Pulkkinen 2007; Airapetian et al. 2020; Temmer 2021; Ilin et al. 2024).

For this reason, it is important to understand stellar flares and what differentiate them from their solar counterparts. However, this is not straightforward, as solar flares are typically studied in high spectral and spatial resolution, while the opposite is true for stellar flares, which are primarily observed in white light, and only more recently with high-resolution spectrographs (e.g., Namekata et al. 2021; Martínez González et al. 2022; Namizaki et al. 2023). As solar flares imprint only faint (Woods et al. 2006; Kretzschmar 2011) or non-detectable (Pietrow et al. 2024a) white-light fluctuations on a disk-integrated scale, direct comparisons have so far only been possible within numerical models (e.g., Allred et al. 2005; Druett et al. 2024). However, this is no longer the case when looking at spectral lines where even relatively weak flares for stellar standards can leave an imprint on a disk-integrated spectrum (see Fig. 1).

Namekata et al. (2021, 2022), Otsu et al. (2022), and Xu et al. (2022) pioneered a pseudo-Sun-as-a-star analysis technique for flares and CMEs by studying line-profile evolutions of spatially integrated spectra of a small region around the event. Here, a difference was seen between the imprint of the flare on the spectra and its position on the disk. Such a relation has already been known to exist between UV and X-ray radiation for solar flares (Woods et al. 2006) and has recently been suggested to also exist for spectral lines in the visible by Yu et al. (2025) through 1D flare simulations using the RADYN code (Allred et al. 2005). If confirmed in observations, such an effect could prove to be a powerful technique for determining the disk position of these events.

However, it was not clear if these patterns found using the pseudo-Sun-as-a-star technique are truly related to the flare location, or whether this is a result of small field-of-view (FOV) integrations, which do not take into account the center-to-limb

variations (CLV) and differential rotation of the rest of the star. Its validity was largely confirmed by the first true Sun-as-a-star flare analysis (Pietrow et al. 2024a) that used the solar telescope (Dumusque et al. 2015) connected to the High Accuracy Radial-velocity Planet Searcher for the Northern hemisphere (HARPS-N; Cosentino et al. 2012) instrument on the Telescopio Nazionale Galileo.

Follow-up studies with such Sun-as-a-star telescopes are limited by their signal-to-noise ratio (S/N) and are primarily sensitive to very strong flares. On the other hand, there is a large collection of flare observations taken with high spatial and spectral resolution in the solar community that have excellent S/N but a limited FOV. Such observations can be processed in a way similar to that of other pseudo-Sun-as-a-star studies to obtain more statistics on flare behavior in a disk-integrated setting. However, we propose adding an additional step to more closely approximate true Sun-as-a-star flare observations. In this work, we apply the Numerical Empirical Sun-as-a-Star Integrator (NESSI; Pietrow & Pastor Yabar 2024) code to synthesize Sun-as-a-star emission from 20 solar flare observations using data with a limited FOV, obtained by the Swedish 1-m Solar Telescope (SST; Scharmer et al. 2003). This work also serves as a pilot study on how the Paranal solar Espresso Telescope (POET; Leite et al. 2024; Santos et al. 2025) can observe flares within its limited FOV, ranging from $1''$ to $60''$, and therefore also explores what can be inferred from partially captured flares.

2. Data and methods

In this work, we made an effort to collect and discuss a statistically significant number of 20 solar flares observed by the SST. These flares were observed in various lines, using the CRisp Imaging SpectroPolarimeter (CRISP; Scharmer et al. 2008) and the CHROMospheric Imaging Spectrometer (CHROMIS; Scharmer 2017). Both instruments are based around a set of two Fabry-Pérot interferometers, allowing for accurate wavelength tuning, and thus can “scan” through a spectral line to get a quasi-simultaneous spectrum at an average spectral resolution $\mathcal{R} \approx 130\,000$. The flare locations are shown in Fig. 2 and the flare characteristics are summarized in Table A.1.

The data used in this work are a collection of observations spanning the period from 2011 to 2024, collected by various institutes for different scientific purposes. As a result, the observations use different line samplings, cadences, and pointing strategies. All sets are reduced by some version of the standard CRISPRED and SSTRED pipelines (de la Cruz Rodríguez et al. 2015; Löfdahl et al. 2021), but there are differences in the output products. Older cubes were saved in the legacy “La Palma cube” format and contain polarimetric fringes and poor intensity calibration. These cubes were also not always rotated in such a way that solar north is up. In these cases, the rotation was performed manually based on the SST turret logs, intensity calibrations were performed, and the cubes were saved into the standard FITS format.

Furthermore, all data is reconstructed using multi-object multi-frame blind deconvolution (MOMFBD; Löfdahl 2002; van Noort et al. 2005), which is known to introduce artifacts in frames with very bad seeing conditions (see, e.g., Fig. 5.4 of Pietrow 2022). This is one reason why observations under such conditions are typically avoided. However, solar flare observations are sufficiently rare that exceptions are made in this case. The MOMFBD artifacts exacerbate the effects of poor seeing on FOV-averaged spectra and cannot be corrected because of the

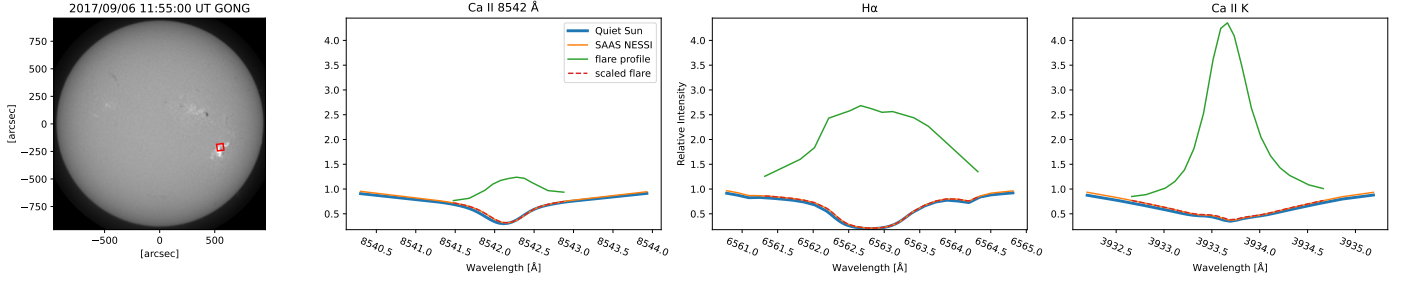


Fig. 1. Comparison of localized flare profiles and disk-integrated Sun-as-a-star profiles. Left: A GONG $H\alpha$ line core image showing a large solar flare (red box) within a field of view (FOV) typical of high-resolution solar observations. Right: The $\text{Ca II } 8542 \text{ \AA}$, $H\alpha$, and Ca II K line profiles at different locations: within the FOV in a quiet region (blue), integrated over the quiet-Sun disk for the Sun as a star (orange), and on the flare ribbon (green). The scaled flare (red dashed) is a simple ratio scaling of the FOV area to the total disk area, while the NESSI profile is the result of injecting the average flare profile (green) into a full-disk quiet-sun profile (blue). All profiles are normalized to their respective quasi-continua. The small difference between the red dashed and blue lines illustrates the stark differences between solar and stellar observations.

legacy origins of the dataset. This leaves recognizable signatures in the spectra, which we discuss and point out in Section 3.

Additionally, each flare is checked for jumps in tracking and bad pixels, and where possible, the data is cropped accordingly to remove these effects. With this, we aim to minimize any instrumental effects on the Sun-as-a-star analysis.

The strengths of solar flares are characterized using the scale by Baker (1970), which uses the peak flux measured in the Geostationary Operational Environmental Satellite (GOES; Menzel & Purdom 1994) 1–8 Å channel to divide flares into one of five classes (A, B, C, M, and X class) where each class represents an order of magnitude jump in flux. While Warmuth & Mann (2016) have shown that this scale does not scale one-to-one with radiated bolometric flare energy, this is generally assumed.

In this case, an X1.0 flare is defined as having 10^{31} erg (e.g., Fig. 2 in Shibata et al. 2013 and Fig. 5 in Maehara et al. 2015). As flares of this type are generally rare, this indicates that the Sun’s flare output is significantly below average, as Pietras et al. (2022) report an average stellar flare strength of approximately X100 (or X10 based on the assumptions of Simões et al. 2024) for G-type stars.

2.1. NESSI

The NESSI code (Pietrow & Pastor Yabar 2024) was created to convert limited FOV solar observations into simulated full-disk Sun-as-a-star observations. This is done using accurate CLV measurements for a given wavelength range to create a solar disk on a polar grid. The line profiles on this grid are then shifted according to a differential rotation law, such as the one presented in Balthasar et al. (1986) and assumed to be constant for all lines. This grid is then integrated to create a quiet-Sun profile of the Sun-as-a-star. Flare observations can be injected by dividing their average spectra by a subfield of the NESSI quiet-Sun disk, matching the size and position of the SST FOV, after which the resulting spectrum is multiplied with the quiet-Sun disk. This makes it as if the SST flare had occurred on the full disk. The process is illustrated in Fig. 1. NESSI works in a similar way to the Spot Oscillation And Planet code (SOAP; Boisse et al. 2012; Dumusque et al. 2014) but relies fully on empirical data.

This approach of creating pseudo-Sun-as-a-star observations is similar to the one presented by Otsu et al. (2022), where small areas on the disk are integrated and normalized by quiet-Sun areas of similar size elsewhere on the disk. However, our approach allows for the preservation of intensities, thus showing how bright and detectable a flare would be in a true Sun-as-a-star

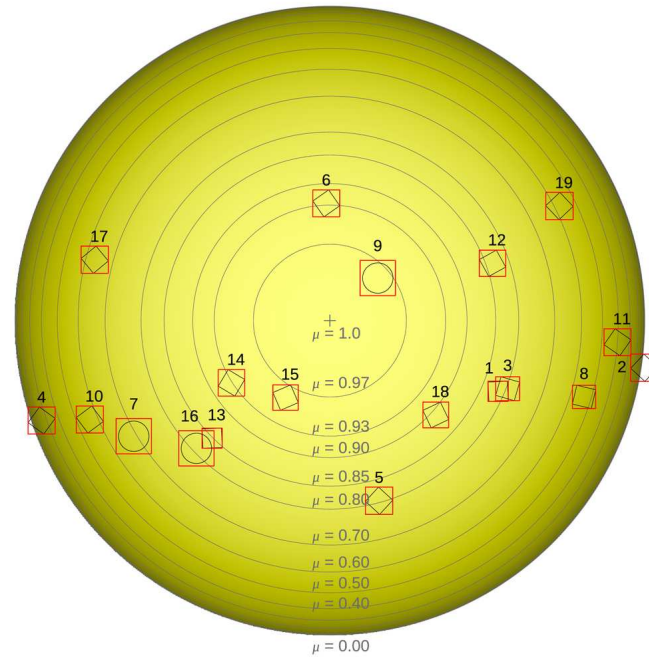


Fig. 2. Flare locations on the solar disk (red boxes) labeled with event numbers from Table A.1. Tilted black squares and black circles (corresponding to Events 7, 9, and 16) approximately match the CRISP or CHROMIS FOV in the COCOPLOTS in Figs. 4–21. Gray concentric circles correspond to directional cosines μ , labeled accordingly, with the disk center marked by a plus sign.

observation such as the one presented in Pietrow et al. (2024a). This method is a digital analog to the observational strategy of the POET telescope, and many of the issues discussed in this work will be relevant to future observations with this telescope. The codes used in the follow-up analysis, the example images, and animations are publicly available at this repository¹, as well as included with this paper.

2.2. Data normalization

We determine the spectral contribution of each FOV by comparing the dataset to a quiet reference region contained within. For each observation, an area containing the “quietest Sun” is manually selected inside one of the frames of the time series, away

¹ <https://github.com/demichieldewilde/solar-flares>

from the peak of the flare. Intensity data over this selected area are averaged to obtain the reference quiet-Sun spectral intensity² as a function of wavelength $I_{\text{QR}}(\lambda)$. The NESSI code is then used to generate a theoretical quiet-Sun profile at this disk location $I_{\text{QR}}^{(\text{N})}(\lambda)$, and the two are scaled to calibrate the observational data to the NESSI disk data. The continuum wavelength is used where available, and otherwise the furthest wing wavelength points are used, as these are less sensitive to flares and other activity signals. The scaling constant α is introduced such that the merit function

$$\chi^2 = \sum_j \left(I_{\text{QR}}^{(\text{N})}(\lambda_j) - \alpha I_{\text{QR}}(\lambda_j) \right)^2 \quad (1)$$

is minimized. This constant α is then used to normalize the data. Hence, the NESSI spectrum can now be directly compared and subtracted from the observed spectra.

We took great caution choosing the quiet reference regions because generally the flares occurred in the vicinity of a sunspot or AR, which therefore is not truly a quiet Sun. This is an intrinsic limitation of small FOV observations. Nevertheless, using a gauge to a theoretical quiet Sun profile makes the method more robust. Further, the evolutionary timescales of spots and other activity in the FOV are much slower than those of the flares. Therefore, their influence in the contrast profile (see below) will largely be mitigated by dividing out the reference spectrum. Further confounding factors caused by using small FOV observations include variations in seeing conditions, and bright (or dark) areas moving into or out of the FOV caused by jumps in pointing.

2.3. Contrast profiles

To study the impact of a flare on an otherwise quiet Sun, we calculated the difference between the observed integrated FOV spectrum and the NESSI spectrum. Both are averaged and subtracted so that

$$\Delta I_{\text{FOV}}(\lambda, t) = \frac{O^{-1}}{A_{\text{FOV}}} \int_{\text{FOV}} I(x, y, \lambda, t) - I^{(\text{N})}(x, y, \lambda) \, dx dy, \quad (2)$$

where A_{FOV} is the FOV area and O , shown in Table A.1, is the fractional overlap estimated mainly between the CRISP FOV and the total flare area. This factor is introduced to approximate the full flare intensity as accurately as possible in the assumption of a linear relation between coverage and intensity. For events with significantly limited spatial coverage in the CHROMIS FOV, the overlap was averaged between the CRISP FOV and the CHROMIS FOV relative to the total flare area. All quantities will be corrected for partial coverage.

This spectral difference is added onto the NESSI full-disk (FD) spectrum, effectively replacing the area that has been subtracted from the observed FOV,

$$I_{\text{FD}}(\lambda, t) = I_{\text{FD}}^{(\text{N})}(\lambda) + \Delta I_{\text{FOV}}(\lambda, t). \quad (3)$$

Therefrom the contrast profile can be defined as

$$C(\lambda, t) = I_{\text{FD}}(\lambda, t) / I_{\text{FD}}^{(\text{N})}(\lambda). \quad (4)$$

This method is similar to the one of Otsu et al. (2022) but with the added benefit of preserving the full-disk intensities, thus

² In the following, quantities representing spectral intensity are distinguished from specific intensities I by the subscripts QR , FOV , and FD , which indicate area integrals over a Quiet-Sun Region, the Field of View, or the Full Disk, respectively.

allowing the measurement of realistic contrast profiles. Many of these will be far below the detection limit of current Sun-as-a-star instruments.

2.4. Noise simulations

We can test how well the synthesized spectra fit full-disk observations by degrading the SST spectra to the resolution of HARPS-N and matching the noise profiles.

We made a case study based on observations of the X9.3 flare, where we compare our synthetic Sun-as-a-star contrast profiles with those of the same flare, which was also observed with the HARPS-N telescope (Pietrow et al. 2024a). Firstly, we match the 5-minute cadence by taking every 20th observation. We do not change the spectral resolution, as the $\mathcal{R} \approx 130\,000$ resolution of SST/CRISP is very similar to the $\mathcal{R} \approx 125\,000$ resolution of HARPS-N. The S/N of the observations are matched next, where we add noise based on the standard deviation of the HARPS-N continuum close to the Ca II K and H α lines. By matching the noise level of HARPS-N both photon and instrumental noise is accounted for. Finally, the resulting profile is multiplied by 2.5 to account for the fact that we capture only about 40% of this flare in our FOV.

The resulting contrast profiles for H α and Ca II K are shown in Fig. 3 in the top and bottom row, respectively. For both lines, the first column shows contrast profiles of the undegraded SST contrast profiles. The second column shows the same profiles degraded to the HARPS-N cadence and S/N, and the final column shows the corresponding HARPS-N profiles.

While the SST data was observed for a much shorter time, we find a strong similarity with the contrast profile shapes and intensities between minutes 10 and 20. After this time, the flare seemingly gets dimmer in the SST frame while it stays bright in the other data. This is consistent with the flaring activity inside and outside of the limited FOV of the SST observations, which captures only around 40% of the flare, i.e., toward the middle of flare's lifetime, most of the bright ribbon feature lies outside of the $60'' \times 60''$ SST FOV.

2.5. Differenced equivalent width

The differenced equivalent width of disk- or FOV-integrated flare observations has been shown to be correlated with large-scale flare evolution as it captures the line broadening and Doppler effects (Namizaki et al. 2023; Otsu et al. 2022).

In Otsu et al. (2022) a quiet FOV of the same size and μ value is used as a quiet-Sun gauge. We instead use the NESSI-generated FOV at the exact flare location, thus avoiding issues with differential rotation. This method works particularly well in regions close to the limb, where a strong gradient in μ is present within the FOV.

Otsu et al. (2022) defined their normalized spectral change for a specific time step t_0 as

$$\Delta S(\lambda, t) = \frac{I_{\text{FOV}}(\lambda, t) - I_{\text{QR}}(\lambda, t_0)}{I_{\text{FD}}(\lambda_{\text{cont}}, t_0)}. \quad (5)$$

In our case, it takes the form

$$\Delta S(\lambda, t) = \frac{\Delta I_{\text{FOV}}(\lambda, t)}{I_{\text{FD}}^{(\text{N})}(\lambda_{\text{cont}})}. \quad (6)$$

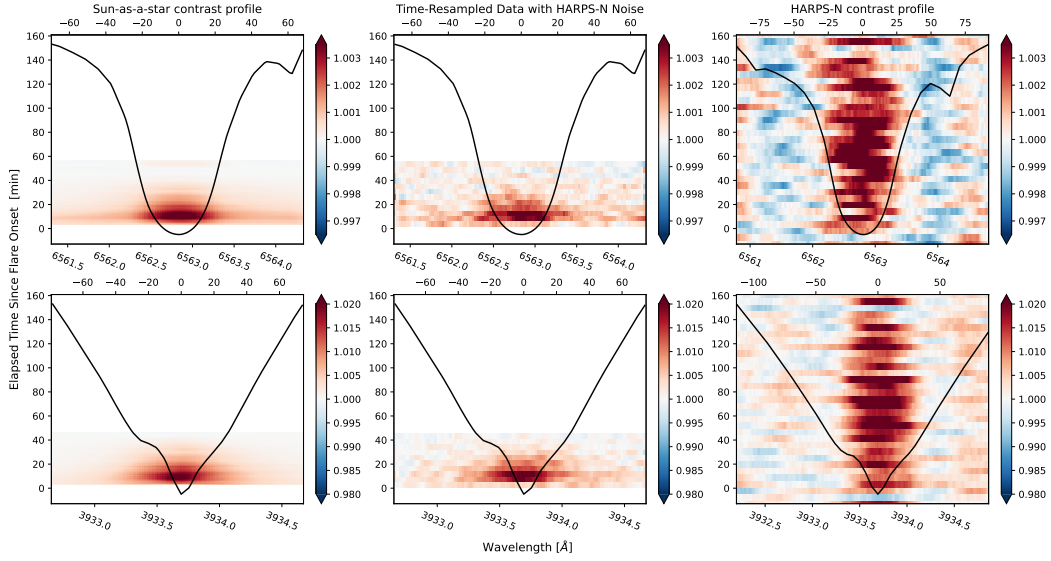


Fig. 3. Construction process of the temporal variation of the Sun-as-a-star contrast profile, $C(\lambda, t)$ (Eq. (4)), with a resolution equivalent to HARPS-N, derived from high-resolution SST observations of the X9.3 flare, listed as Event 1 in Table A.1, for H α (top row) and Ca II K (bottom row). Each panel presents the contrast profile relative to quiet-Sun profiles (black curves). Color bars denote the values of $C(\lambda, t)$. Left column: Sun-as-a-star contrast profiles generated using the NESSI code. Middle column: Same as the left column but resampled to the HARPS-N temporal resolution of 5 minutes and degraded by adding normally distributed noise with a standard deviation estimated from the wings of line profiles observed by HARPS-N. Right column: Contrast profiles of H α and Ca II K reconstructed from HARPS-N observations of Event 1, shown also in Fig. 4.

Integrating over this quantity over the interval $\Delta\lambda = \pm 0.5 \text{ \AA}$ yields the differenced equivalent width ΔEW as

$$\Delta EW = \int_{\lambda_0 - \Delta\lambda}^{\lambda_0 + \Delta\lambda} \Delta S(\lambda, t) d\lambda, \quad (7)$$

with λ_0 the wavelength of the spectra line in question. The ΔEW values are then scaled to facilitate comparison between lines with different widths and sensitivities to activity. The differenced equivalent width corresponds to the total change in the spectral line profile (Otsu et al. 2022). For convenience, the relative values, denoted as δEW , have been adopted. They are normalized with respect to the reference value $|\Delta EW(t_0)|$ of particular line at the SST start time t_0 (Table A.1), such that $\delta EW(t) = \Delta EW(t)/|\Delta EW(t_0)|$. These normalized values are shown in Figs. 4–21 alongside the ad hoc normalized soft X-ray flux measured by GOES in the 1–8 Å passband. In some cases $\delta EW(t_0) = -1$ (see, e.g., Fig. 7) causes the δEW line to be separated from the other δEW lines starting at 1. In these instances, as noted in the figure captions, an offset has been applied to the δEW curve for improved clarity.

2.6. Residual analysis via Voigt profile subtraction

We analyze spectral residuals using a method similar to that of Ma et al. (2024), in which a Voigt profile is fitted to, and subtracted from, the contrast profiles (Eq. (4)). This approach has proven effective in isolating subtle features by removing the dominant central enhancement – or, in some cases, central absorption – visible in contrast profiles. The Voigt profile is defined as

$$V(\lambda, \sigma, \gamma) \equiv \int_{-\infty}^{\infty} G(\lambda', \sigma) L(\lambda - \lambda', \gamma) d\lambda', \quad (8)$$

where $G(\lambda, \sigma)$ and $L(\lambda, \gamma)$ denote the centered, area-normalized Gaussian and Lorentzian functions, respectively:

$$G(\lambda, \sigma) \equiv \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\lambda^2}{2\sigma^2}}, \quad L(\lambda, \gamma) \equiv \frac{\gamma}{\pi(\gamma^2 + \lambda^2)}. \quad (9)$$

At each time frame t , the contrast profile $C(\lambda, t)$ is modeled by the function

$$1 + \alpha(t) V(\lambda - \beta(t), \sigma(t), \gamma(t)), \quad (10)$$

where α, β, σ , and γ are time-dependent fitting parameters. Subtracting the fit yields the residual spectrum:

$$R(\lambda, t) = C(\lambda, t) - 1 - \alpha(t) V(\lambda - \beta(t), \sigma(t), \gamma(t)). \quad (11)$$

Residuals $R(\lambda, t)$ are visualized using color maps, overlaid with contour lines of the fit, see Eq. (10). Particular care was taken to ensure a robust fit to the core of each contrast profile. Initial guesses for the parameters α, γ , and σ were determined manually for the first frame of each event and subsequently propagated using a five-frame rolling average. Despite this, the fitting procedure was sensitive to initial conditions and did not always yield reliable results, for example, for the Fe I 6173 Å line in the Events 5 and 19 (Figs. 8 and 21, respectively).

A small number of outlier frames occasionally disrupted the fitting sequence or introduced artificial features into the residuals. We therefore advise cautious interpretation of the residuals, particularly when they exhibit anomalous shapes. Nevertheless, the model generally captured the temporal evolution of the core of the contrast profile effectively.

3. Results and discussion

This section presents a detailed analysis of Sun-as-a-star spectral signatures from 20 solar flares in 19 data sets, ranging in class from X9.3 to C1.2, observed by the SST between August 2011 and September 2024. We begin with an overview of unique spectral features imprinted in Sun-as-a-star spectra, which are specific to individual events, after which we discuss the individual events in Table A.1. Thereafter, we present a scale law between intensity and core intensity modulation.

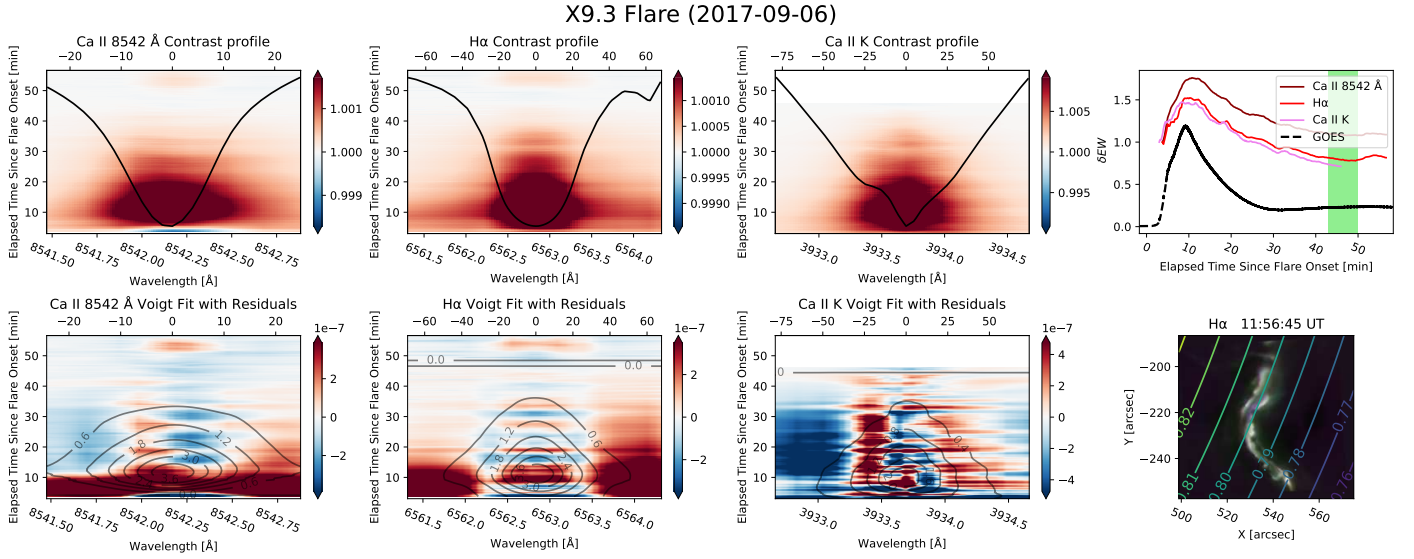


Fig. 4. Event 1. Top row: Temporal variations of the Sun-as-a-star contrast profile, $C(\lambda, t)$ (Eq. (4)), for the Ca II 8542 Å, Hα, and Ca II K lines, respectively. Each panel shows the contrast profile relative to quiet-Sun profiles (black curves) and the relative differenced equivalent widths δEW (top right panel), integrated over $\Delta\lambda = \pm 0.5$ Å around the line centers (Eq. (7)) and normalized relative to the $|\delta EW(t_0)|$ value of particular line at the SST Start time t_0 (Table A.1). The green bar marks the reference time span Δt , which serves as the reference for the contrast profile $C(\lambda, t)$. The GOES X-ray flux in the 1–8 Å range is overplotted after ad hoc scaling. Color bars indicate the values of $C(\lambda, t)$. Bottom row: Temporal variations of the model function (Eq. (10)) for the Ca II 8542 Å, Hα, and Ca II K lines, represented by black contours, plotted over the residuals $R(\lambda, t)$ of the fits (Eq. (11)). The contours are labeled by spectral intensities normalized to the quiet-Sun continuum spectral intensity. The contour labeled 0 approximately corresponds to the midpoint of the time span Δt , represented by the green bar in the δEW panel. The dashed contours indicate negative values. Color bars indicate the values of $R(\lambda, t)$. The top x-axes display velocities in km s^{-1} corresponding to Doppler shifts relative to the line centers. Bottom right panel: The cocoplot overlaid with contours of the respective directional cosines μ (Druett et al. 2022).

3.1. Feature summary

The contrast and residual profiles of the analyzed flares (Eqs. (4) and (11)) reveal global features shared by almost all events, along with a few less frequent yet distinct signatures that appear only in specific subsets of flares. From these profiles, we discern two sets of spectral features. Set 1 (Features 1–4) – physical features that should be robustly detectable in disk-integrated observations with a high enough signal-to-noise-ratio. Set 2 (Features 5–6) – spurious or misinterpreted features that imitate true detections but originate from the detection algorithm or from particular conditions of the flare. Particular attention is given to the detectability of CMEs in the stellar context.

3.1.1. Physical features

Our investigation finds the following features to originate from processes on the Sun, which can be interpreted physically. We distinguish them from other features.

Feature 1: Core intensity modulation

Core intensity modulation is the most frequent feature of flare activity, detected across the full range of flare strengths. It manifests around the flare peak as the core intensity enhancement in all considered chromospheric lines except He I D3, where it appears as an absorption feature instead. The dark red contrast profiles in the top row of Figs. 4 and 6 are a good example of the former, while the dark blue region at the center of the top right panel of Fig. 10, exemplifies the latter.

The specific flare behavior of the He I D3 line is due to the photoionization-recombination mechanism populating the

corresponding levels (Libbrecht et al. 2019). Consequently, the line initially appears in absorption before later transitioning into emission. The unambiguous variation in the intensity of the core is only absent in Event 8 (Fig. 11) most likely due to the small spatial overlap between the flare and the FOV (Table A.1, column 8). The corresponding residual profiles often but not always exhibit significant positive excess between wings of the contrast profile and the model function (e.g., Figs. 4 and 6), which suggests broadening of emission lines around the flare peak. This is characteristic for strong chromospheric lines.

Feature 2: Redshifted emission

Several events display a transient, red-shifted emission component that becomes most prominent at the flare peak and fades as the flare progresses. This signature is evident in Event 3 (Fig. 6; Ca II 8542 Å, Ca II K), Event 5 (Fig. 8; Ca II 8542 Å), Event 6 (Fig. 9; Ca II 8542 Å), Event 7 (Fig. 10; Hα, Hβ), and Event 17 (Fig. 19; Ca II 8542 Å, Ca II K). We attribute this temporary red shift to down-flowing, cool, condensed plasma that drains along flare loops into the flare ribbons, which are largely unobscured by overlying filaments (see the corresponding animations¹). This phenomenon is commonly referred to as coronal rain (see e.g., Pietrow et al. 2024b). All of these events lie at heliocentric directional cosines of $\mu \approx 0.93$ – 0.64 (Table A.1), a range that maximizes the line-of-sight projection of the flow velocity and thereby enhances the red-shifted components. This interpretation is in line with the findings of Yu et al. (2025). A redshifted emission – referred to as red asymmetry – is evident in the Hα profile associated with a superflare on YZ Canis Minoris, reported by Namizaki et al. (2023, panel (d) in Fig. 3).

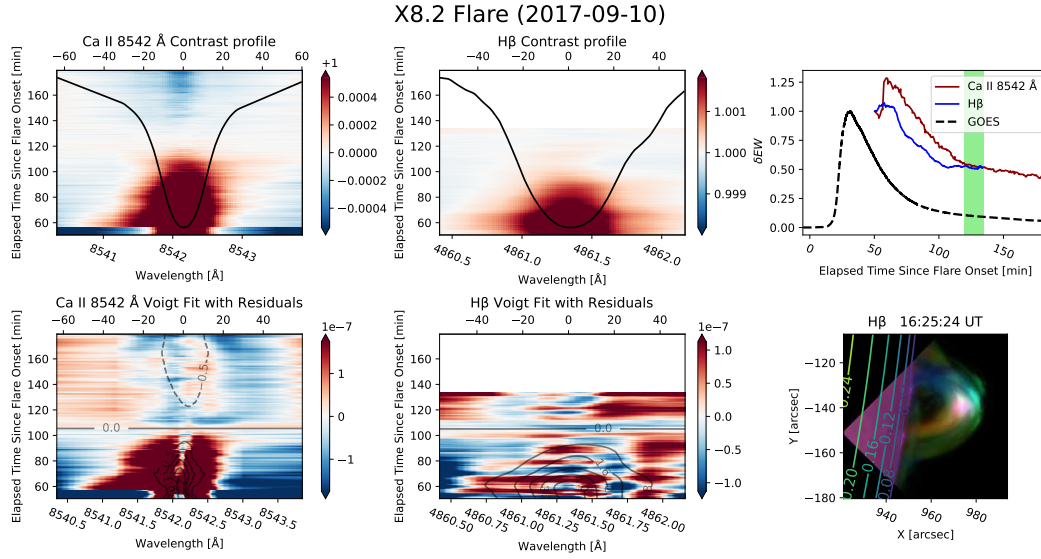


Fig. 5. Event 2. Same as Fig. 4 but for Ca II 8542 Å and H β disregarding Fe I 6302 Å and Ca II H & K. In the top left panel, the colorbar values of $C(\lambda, t)$ are offset by +1, as indicated at the top of the colorbar. This offset is also applied in some of the subsequent figures.

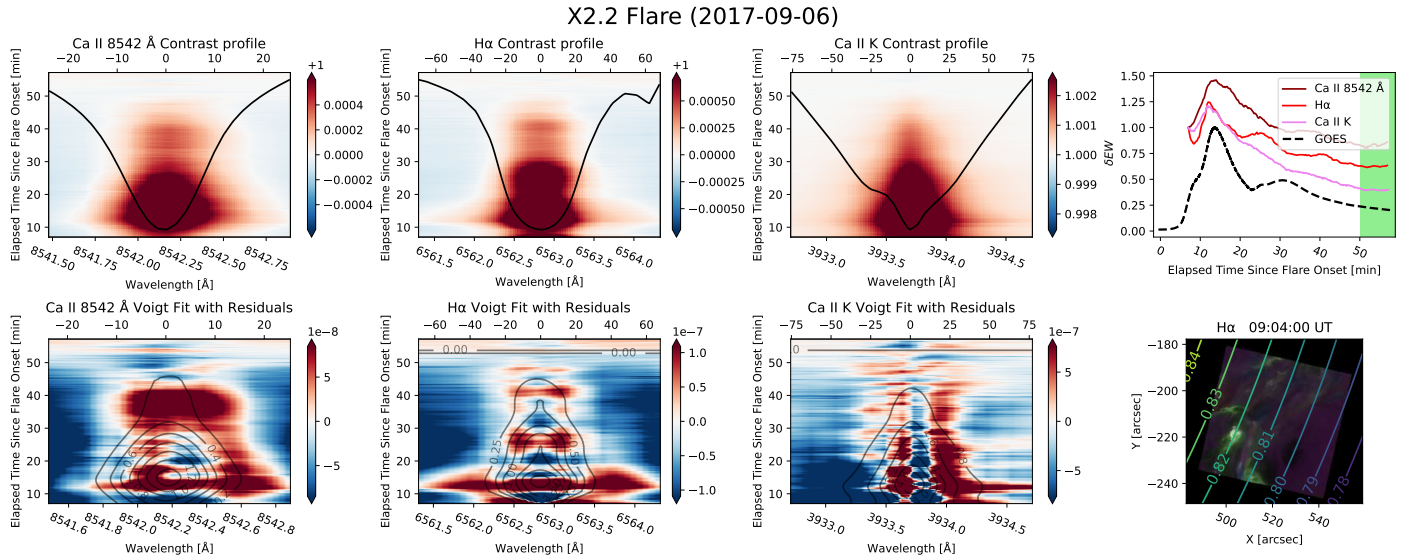


Fig. 6. Event 3. Same as Fig. 4.

Feature 3: Imprints of filaments and flare loops

A comparatively rare yet distinctive signature is observed in Events 8, 11, and 18 (Figs. 11, 14, and 20). It appears as a blue absorption feature in the contrast profiles and residuals and can be present in the blue and sometimes the red wings of these profiles. Inspection of the associated H α animations¹ indicates that this behavior arises when dynamic structures (flare loops in Event 8 and rising filaments in Events 11 and 18) partially obscure the underlying flare ribbons. Remarkably, these spectral signatures resemble those associated with an eruptive filament from a superflare on a solar-type star and a C5.1-class solar flare and filament eruption (Namekata et al. 2021, see panels c and d in Fig. 1, and panel b in Fig. 2, respectively).

Feature 4: Temporal offset between δEW and GOES peaks

Feature 1 is accompanied by an enhancement in the normalized differential equivalent width (δEW) of the contrast profiles, as

illustrated in the upper right panels of Figs. 4–21. In Events 7, 10, 15, 17, and 18 (Figs. 10, 13, 17, 19, and 20, respectively), the δEW enhancement appears to precede the peak in the GOES data. In contrast, for Events 1, 3, and 6 (Figs. 4, 6, and 9, respectively), the peak times of δEW and the GOES data appear to coincide. Only in Event 9 (Fig. 12) does the δEW peak clearly lag behind the GOES peak. A definitive assessment of the temporal relationship between the δEW and GOES peak times will be presented in a separate dedicated investigation. For the remaining events, incomplete temporal coverage precludes a reliable evaluation of this relationship.

3.1.2. Spurious features

We attribute these features primarily to instrumental and seeing-induced effects, which should be carefully considered in future studies involving a limited FOV. We highlight these features as they can be misinterpreted as physical features.

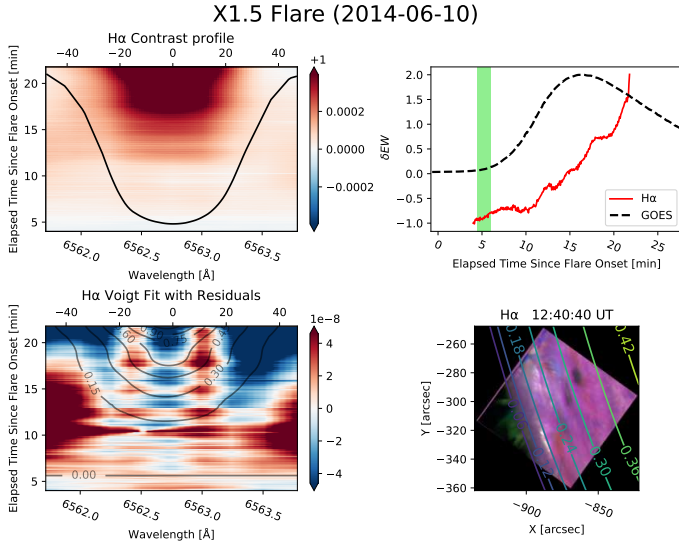


Fig. 7. Event 4. Same as Fig. 4 but for H α .

Feature 5: False quasi-periodic oscillations

A closer inspection of the residual profiles for Events 1–7 and 17–19 (Figs. 4–10 and 19–21, respectively) reveals quasi-periodic patterns in the contrast profiles and residuals (appearing as alternating blue and red) that are apparent in some or all of the spectral lines. An investigation into their origin shows that they are either caused by seeing-induced, quasi-periodic smearing of bright flare features (e.g., Event 1), or by minor tracking issues that result in parts of the flare intermittently drifting in and out of the field of view during the time series (e.g., Event 2). These effects reflect limitations inherent to observations with a restricted field of view and are not expected to occur in stellar observations, where spatial resolution is not a factor.

Feature 6: False profile modulation and abrupt jumps

Events 2, 7, 8, 9, and 15 (Figs. 5, 10, 11, 12, and 17, respectively) exhibit brief anomalies in their contrast profiles at the very start of their time series. This anomaly is a processing artifact – an unrealistically weakened line core, thus rendered in dark blue. It arises because the reference interval used for normalization – indicated by the green bars in the upper-right panels of respective figures – was chosen after the flare peak, combined with the particular shape of the reference line profiles. In addition to this initial spurious modulation, the residuals of Events 2 and 9 (Figs. 5 and 12) show abrupt jumps caused by small telescope repointing undertaken to keep the flare optimally centered within the field of view.

3.1.3. Detectability of CMEs

In the context of the rapidly expanding literature on stellar CMEs (e.g., Veronig et al. 2021; Namekata et al. 2021; Leitzinger et al. 2022, 2024; Leitzinger & Odert 2022), this subsection focuses on identifying physical CME signatures in Sun-as-a-star observations and spurious, CME-like features. Distinguishing between the two is crucial for robust stellar-CME detection.

An inspection of the [SoHO/LASCO CME Catalog](#) (Gopalswamy et al. 2009) revealed ten events (1–5, 7, 9–11, and 17 in Table A.1). Thus, 53% of the flares in our sample produced

a cataloged CME. Among these events associated with CMEs, only Event 11 (Fig. 14) exhibits the typically associated contrast and residual profiles (a blue-wing absorption feature, occasionally mirrored in the red wing) despite its associated CME being the second weakest of the set. Within the SST spectral window, these signatures closely resemble those of CME events (5)–(7) in Otsu et al. (2022, Table 1; panels (a) of Figs. 10, 13, 15), all of which followed filament eruptions. While CMEs can occur without an accompanying flare it is believed that strong solar flares typically have associated CMEs (e.g., Yashiro & Gopalswamy 2009). However, our data reveals no common spectral fingerprint shared by all CME-associated events. On top of that, all but one of these events showed no sign of the classical CME-Doppler signature in the chromospheric spectral lines. However, we caution that this could be a result of the limited FOV of the SST, which simply does not capture the full region.

Conversely, nine flares (6, 8, 12–16, 18, 19) show no cataloged CME (Table A.1), underscoring that flare occurrence alone is an unreliable CME predictor. Moreover, Doppler signatures very similar to those often associated with CMEs have been observed in Events 8 and 18 (Figs. 11 and 20). In both cases, gravitationally bound up-flows cause the Doppler signatures. These false positives, along with the false negatives from flares with associated CMEs, warrant further research into the accuracy of the association between CMEs and the corresponding Doppler features.

3.2. Individual event summaries

In this section, we discuss each event in detail and list the causes for variations in the disk-integrated contrast profiles, residual profiles, and δEW s derived from NESSI. These are shown together with a representative image of the flare and lines showing its location on the disk. Each subheading is listed between Event 1 to 19. The overall findings of this section were listed in the Feature summary above and are recapped in the Conclusions.

Observations made in the He I D3 and iron lines are shown in a different colorbar than the rest to differentiate them from the optically thick chromospheric lines. In the case of He I D3 there is also no limb darkening data available to process the lines with NESSI. As a result, we present a simple FOV-integrated profile.

Each flare is accompanied by its GOES and δEW s curves, to better illustrate potential delays between the different lines.

Each FOV is displayed as a Color-Collapsed PLOTS (COCOPLOTS; Druett et al. 2022), which encode spectral information into color by multiplying the spectra with three offset Gaussians which are then loaded into the R, G, and B channels of the image. We refer the reader to the paper for more examples of this method. Videos of the events are provided in the supplementary materials, showing a time series of the flare in each spectral line, along with the disk-integrated profile.

Event 1: An X9.3 flare on 2017 September 6

An X9.3 flare occurred in the active region NOAA 12673 on 2017-09-06 at ~11:53 UT. Approximately 40% of the flare ribbon area was captured in the FOV of the SST, and therefore, we scaled the recorded flare emission by a factor of 2.5 before passing it onto NESSI as described in Section 2.3. The average μ value for the flare is 0.82. The flare was associated with a Halo CME with a recorded velocity of 1571 km s^{-1} and CME-driven shock that intercepted the Earth causing a significant space weather event (e.g., Yu et al. 2024). This flare was first described in Quinn et al. (2019).

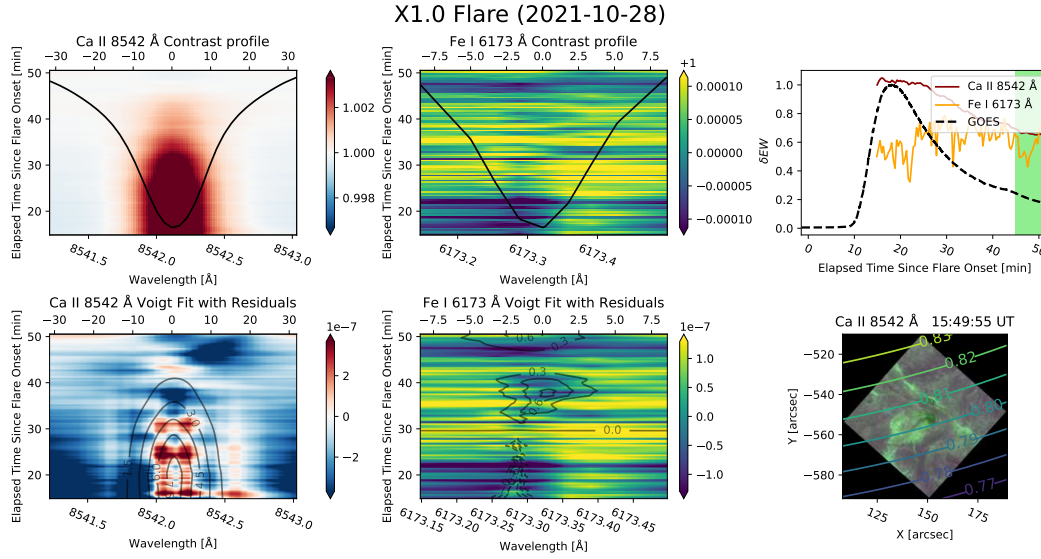


Fig. 8. Event 5. Same as Fig. 4 but for Ca II 8542 Å and Fe I 6173 Å. The δEW of Fe I 6173 Å has been offset by 1.5 for better comparison.

Fig. 4 shows contrast profiles for the spectral lines in the X9.3 flare, with contrast taken relative to the time frames shown with a green bar in the δEW panel. Note that a zero residual does not indicate a flat-line profile, rather no difference to the reference profile used. The Ca II K line appears to have a significantly different contrast level with a much higher sensitivity to small-scale effects.

The shape of all three contrast profiles are similar with Ca II 8542 Å showing the strongest red asymmetry, showing the increased sensitivity to Doppler shift at high wavelengths, given $\Delta\lambda = v_0\lambda_0/c$. A clear temporal offset between the δEW peaks can be seen.

In the residual profiles, more structure can be seen. In H α we see an emissive (red) blueshifted emission lasting roughly 15 minutes, as well as a longer-lasting redshifted emission for about 30 minutes, which weakens considerably after 20. The former coincides with the formation of the flare arcade which has material in emission in these lines moving up and down its loops, while the latter also coincides with the formation of the flare ribbon which compresses the atmosphere causing a redshift until it expands out of the FOV around 30 minutes. In Ca II K we see a similar emissive blue, near-wing enhancement that lasts for 30 minutes in a reasonably stable state. The emission from redshifted material has high velocities early in the flare, and slowly decreases with a similar timescale to the slowing down of the ribbon expansion. After the 30 minute mark, a faint signal showing increasing emissive blue and red shifts can be seen which seems to be connected to flows connected to areas outside of the FOV. We believe that the pulsations are not associated with true quasi-periodic pulsations, but are due to variations in seeing conditions which average out small areas with high Doppler shifts, and move bright regions near the edge of the image in and out of the FOV.

Event 2: An X8.2 flare on 2017 September 10

An X8.2 flare occurred in the active region NOAA 12673 on 2017-09-10 at ~16:30 UT. Approximately 50% of the flare ribbon area was captured in the FOV of the SST. The average μ value for the flare is 0 as the flare occurred very close to the limb and the associated emission comes primarily from the arcade that extends beyond it (see Fig. 5, lower right panel). A very strong

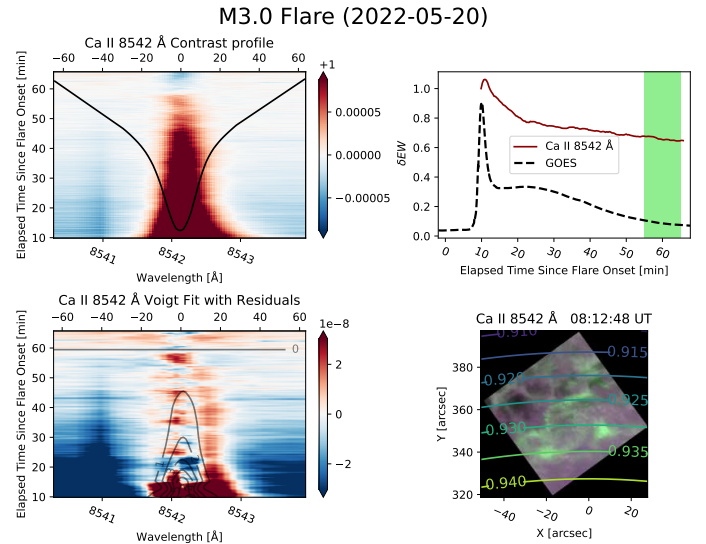


Fig. 9. Event 6. Same as Fig. 4 but for Ca II 8542 Å.

halo-CME of 3163 km s⁻¹ is associated with this event. This flare was first described by Kuridze et al. (2020).

The contrast profiles and δEW s show a very stable increase in emission, which is visible for longer in Ca II 8542 Å than H β likely due to the higher contrast in emissivity caused by the flare in these lines (e.g., Capparelli et al. 2017). Additionally, a sharp jump can be seen in the H β profiles early in the time series, this is due to a change made in the observing program where the Ca II H & K lines were removed from the observational cycle to increase the cadence of H β . During this change, the FOV jumped and excluded part of the flare arcade.

The H β residuals show a decreasing emissive blueshift and enhancement, and an increase in red-wing emission. This is an observational effect, as the arcade is slowly moving out of the FOV due to improper tracking, with the drift over time gradually cutting off the part of the arcade flows with blueshifts, while not affecting the red part. A similar trend can be seen in the contrast profiles of Ca II 8542 Å. If not for these effects, we would expect a very stable increase over the flare's lifetime.

M2.5 Flare (2023-06-09)

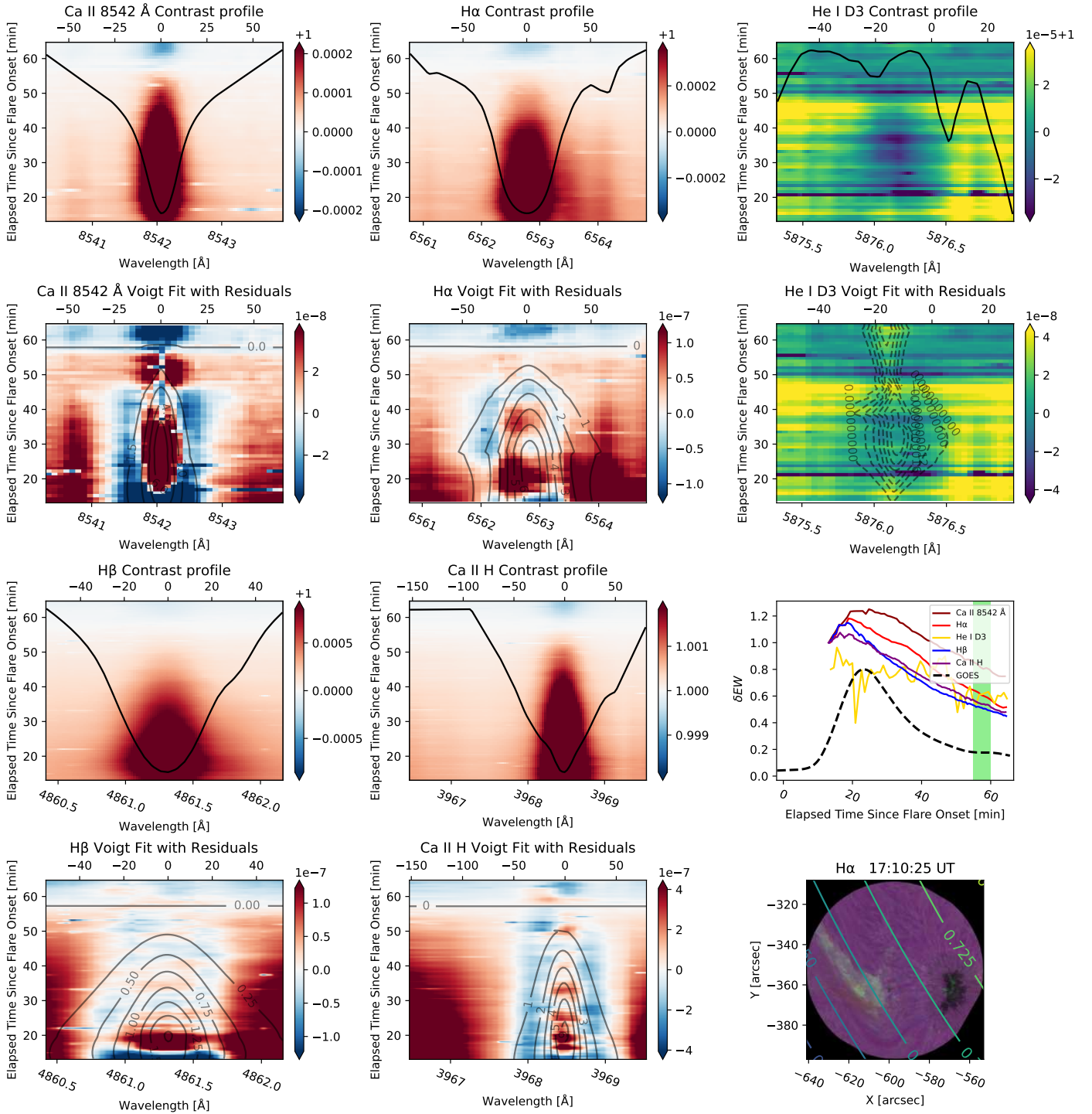


Fig. 10. Event 7. Same as Fig. 4 but for Ca II 8542 Å, Hα, He I D3, Hβ, and Ca II H. In the top right panel, the absorption features in the quiet-Sun profile (black curve) are blends of multiple telluric H₂O and solar metallic lines (see Fig. 2 in Libbrecht et al. (2017) and the top panels of Fig. 4.4 in Libbrecht (2019)). The He I D3 contrast profile corresponds to the dark region approximately within the ranges 5876.00–5876.50 Å and 25–45 min. The colorbar values of $C(\lambda, t)$ are on the order of 10^{-5} and offset by +1, as indicated at the top of the colorbar as $1e-5+1$. This formatting is also used in some of the subsequent figures. In the right column, third panel from the top, the δEW curve of He I D3 has been offset by 1.8 for better comparison.

Event 3: An X2.2 flare on 2017 September 6

An X2.2 flare occurred in the active region NOAA 12673 on 2017-09-06 at ~09:00 UT, three hours before the X9.3 flare discussed in a previous section (for discussion of the relationship between

these flares see Liu et al. 2018; Pietrow et al. 2024a). Approximately 50% of the flare ribbon area was captured in the FOV of the SST. The average μ value of the flare is 0.8. The SST data associated with this flare was first published by Vissers et al. (2021). A slow-moving CME of 391 km s⁻¹ is associated with this event.

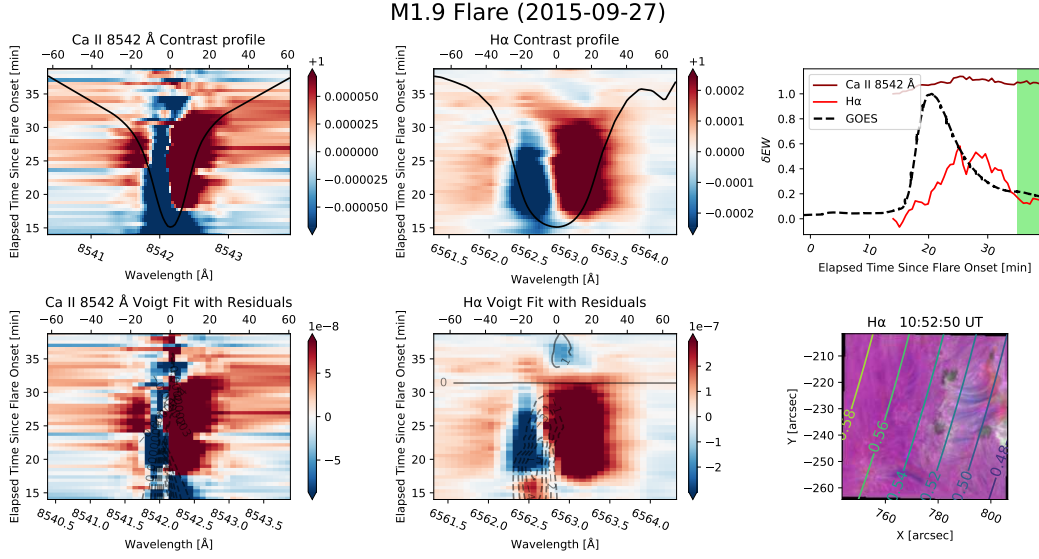


Fig. 11. Event 8. Same as Fig. 4 but for Ca II 8542 Å and H α . The δEW of H α has been offset by 1 for better comparison.

The GOES curve shows that this is a complicated event with the impulsive increase slowing significantly at around 10 minutes before increasing strongly again and reaching the peak at 15 minutes. A subsequent peak can also be seen just beyond 30 minutes, suggesting that several bursts of reconnection may have occurred. The behavior in the δEW of the H α line seems to track the GOES evolution, with the second peak around 25 minutes, and the third around 40 minutes. However, when comparing to SDO, the secondary GOES peak appears to happen outside of the FOV. The peak at around 25 minutes in H α is due to the disappearance of a clump of evaporating material that hung partially over the flare ribbons, absorbing some of this emission, similar to Event 1 in Otsu et al. (2022). When it disappeared, more of the light passed through. Such absorption features are visible in the wings of the residual profiles, seen as dark blue patches in the far wings from 20 to 30 minutes. The peak at 40 minutes seems to be due to poor seeing. These examples highlight that overlying cool material overlapping the flare ribbons in the line of sight can cause significant apparent Doppler shifts in the net flare emission, without any strong signal present from within the ribbons themselves. Such emission should therefore be treated with caution and not necessarily taken to imply the presence of a CME.

Event 4: An X1.5 flare on 2014 June 10

An X1.5 flare occurred in the flare-prolific active region NOAA 12087 on 2014-06-10 at ~12:50 UT. The flare was associated with a large 925 km s⁻¹ CME. Approximately 75% of the flare ribbon area was captured in the FOV of the SST. The flare is located very close to the solar limb, and the average μ value of the flare is 0.14.

The flare ribbons themselves produce strong broad enhancements in the net H α emission, seen as positive (red) contrast across the wavelength range in the Voigt residuals (see Fig. 7). In particular, this enhancement is noticeable in the wings of the profiles, seen as enhancements at times of 8 to 16 minutes. Coronal rain showers manifest in the H α line spectra later in the observational sequence, which appear to manifest in the negative (blue) Voigt residuals at times from 18 minutes onward. Again, the pulsations in intensity appear to relate to changes in seeing conditions rather than any quasi-periodic flare processes.

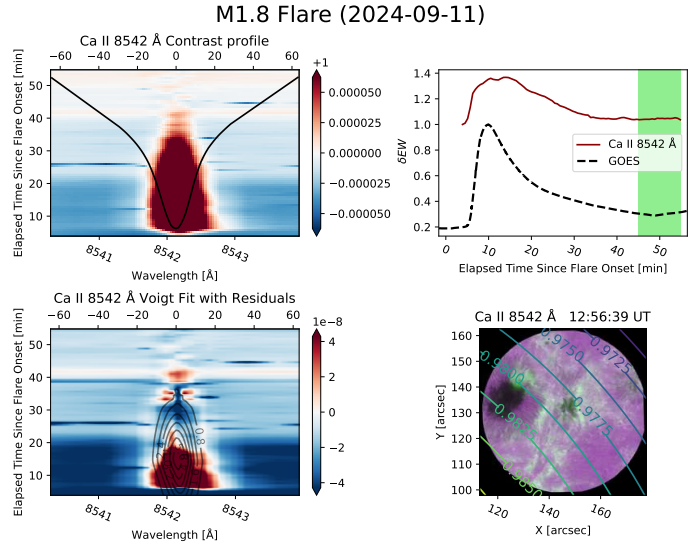


Fig. 12. Event 9. Same as Fig. 4 but for Ca II 8542 Å.

Event 5: An X1.0 flare on 2021 October 28

An X1.0 class flaring event occurred on 2021 October 28 around 15:17 UT. The flare happened in the active region NOAA 12887 with a μ -value 0.804 and was observed in the Ca II 8542 Å and Fe I 6173 Å spectral lines with a 21.6-s cadence. Approximately 10% of the flare ribbon area was captured in the FOV of the SST. The flare was associated with a large 1519 km s⁻¹ CME, although this occurred far from the FOV pointing.

This flare occurred after a filament eruption and consisted of two main parallel flare ribbons, with some smaller flaring ribbons around them. These later merged into a composite ribbon (Yamasaki et al. 2022; Guo et al. 2023). The SST FOV centered on a rather dynamic part of the flare (Fig. 8), as the southern ribbon sweeps across this area at minute 11 (before the start of the SST observation) and then disconnects from the main ribbon at minute 16 (around the start of the SST observation) and starts dying down. The flare ribbon has two further small expansions around minutes 25 and 30, after which the emission (Fig. 8, top right panel) rapidly decays and small upflows and

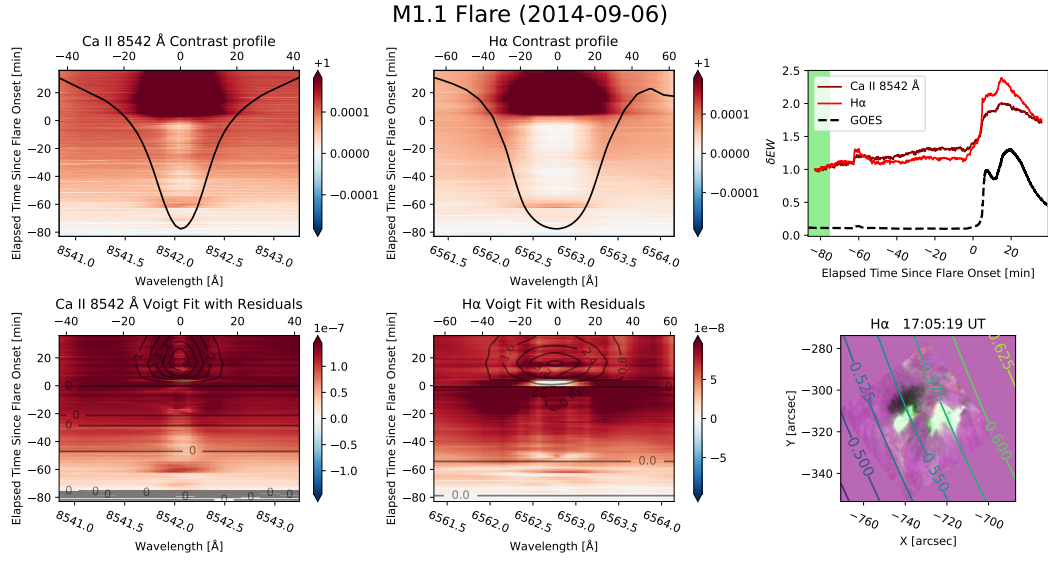


Fig. 13. Event 10. Same as Fig. 4 but for Ca II 8542 Å and Hα.

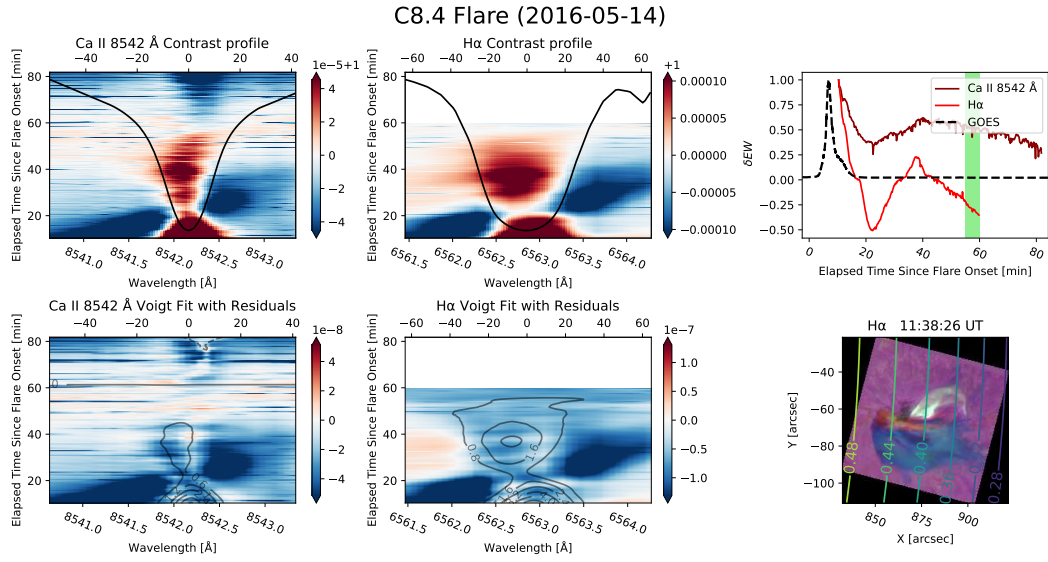


Fig. 14. Event 11. Same as Fig. 4 but for Ca II 8542 Å and Hα.

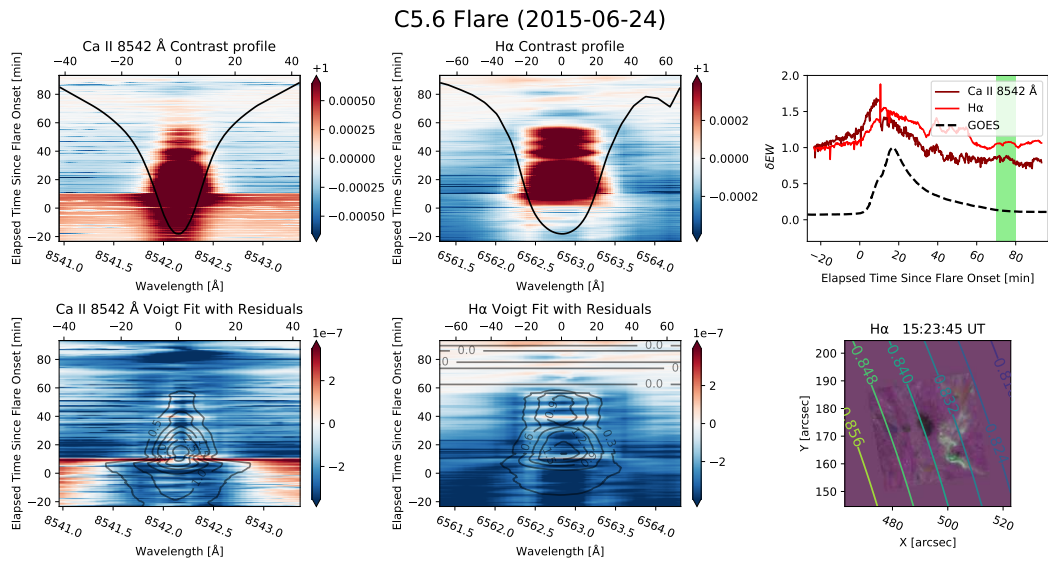


Fig. 15. Event 12. Same as Fig. 4 but for Ca II 8542 Å and Hα.

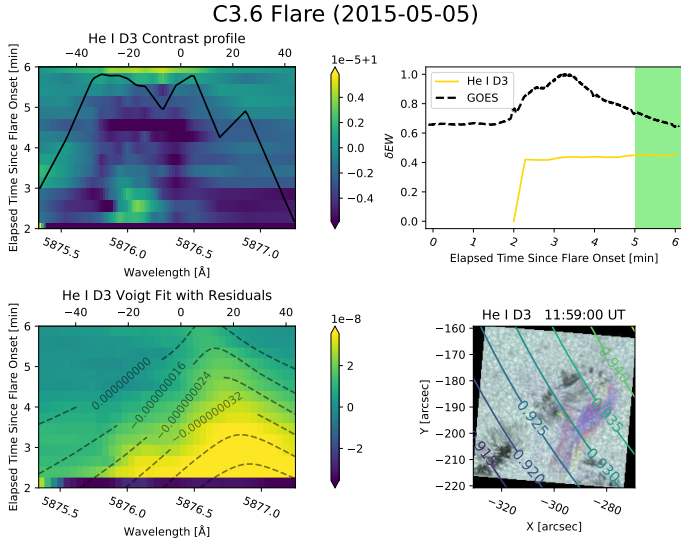


Fig. 16. Event 14. Same as Fig. 4 but for He I D3. In the top left panel, the absorption features in the quiet-Sun profile (black curve) are blends of telluric H_2O and solar metallic lines (see Fig. 2 in Libbrecht et al. (2017) and the top panels of Fig. 4.4 in Libbrecht (2019)). The δEW of He I D3 has been offset by 1.

coronal rain become visible. The enhancements to emission on the red and blue sides of the line core are due to line broadening caused by the flare heating the lower atmosphere, and the expanding front of the flare ribbon causes red-shifted emission enhancements seen in the Voigt residuals at wavelengths around 8542.6 Å (Fig. 8, bottom left panel).

In the iron line, some red-shifted emission can be seen starting at 25 minutes which can be attributed to strong flows in the rapidly evolving light bridge crossing the spot.

Event 6: An M3.0 flare on 2022 May 20

An M3.0 flare occurred in the active region NOAA 13014 on 2022-05-20 at ~07:35 UT. At the first frame of observation, almost full capture of the ribbon area at that time is achieved. However, in the evolution of the flare the ribbons expand outwards partially leaving the FOV. We have approximated this by setting overall 90% ribbon area capture. The flare is near the center of the solar disk, and the average μ value of the flare is 0.927. No CME is associated with this event.

The observation starts at the peak of the flare in the GOES signal and a regular decay in the line enhancement is seen from then onward, both in the contrast profile, Voigt contour lines, and in the normalized differenced equivalent width (see Fig. 9). The GOES curve has a secondary plateau which is only visible in the residuals of the Voigt fit. At the peak of the flare, the ribbon is concentrated and shows strong line center enhancements on the flare ribbon, this produces a central reversal in the line core of the net (NESSI) emission profile. The amount of central reversal decreases between 10 to 20 minutes, causing strong changes to the fitting parameters for the Voigt residuals. Thereafter, the profile contains a double-peaked reversal similar to that of the Ca II H & K lines, and this is consistently redshifted throughout the flare's lifetime. There is also some blueshifted material evident in the video COCOPLOTS during the time span 10–20 minutes and these appear to be associated with the contrast profile and Voigt residuals showing a strong negative value at around 8541 Å. We note that this flare has no associated CME.

This flare has a very similar contrast profile to the 1D simulations for flares close to the disk center shown in Yu et al. (2025).

Event 7: An M2.5 flare on 2023 June 9

An eruptive M2.5 flare occurred in the active region NOAA 13331 on 2023-06-09 at ~16:48 UT. Approximately 40% of the flare ribbon area was captured in the FOV of the SST/CRISP (Ca II 8542 Å, H α , and He I D3), with slightly less over the SST/CHROMIS (Ca II H and H β) FOV. The average μ value of the flare is 0.688. The event has an associated CME with 651 km s⁻¹. The analysis is displayed in Fig. 10.

The times of maximum contrast profile enhancements in different optically thick chromospheric lines are again offset. The peak occurs earliest in Ca II K (typically forms the highest in the atmosphere) and then H α and H β , and the latest peak is seen in Ca II 8542 Å (typically the lowest forming of these lines). The contrast in the Helium line is extremely low, the low level of line core absorption that is present in the contrast profiles peaks tens of minutes after all other lines. In the resolved images as the flare ribbon expands we see dimming, followed by some brief brightening, and a prolonged period of darkened absorption in the line center. This is in general agreement with the theoretical description provided by Kerr et al. (2021).

Viewing the spatially resolved spectral data, we note that in the H α , H β , and Ca II H images and profiles there is strong emission at the start of the flare in the red wing as the flare ribbon forms and compresses the chromosphere, as in Druett et al. (2017) and Pietrow et al. (2024b). While for H α this emission covers wavelengths where there is a telluric line (6564 Å), the resolved signal is clearly dominated by the flare ribbon.

A fast-moving upflowing jet is visible from near the sunspot (−570'', −370'') from 30 minutes up to about 50 minutes, which absorbs the underlying emission. This jet is also visible in the resolved images of the other lines, but not clear in the contrast profiles or Voigt fits. It is possibly merged with the Voigt fit residuals found around the core emission. In helium the flare ribbon is visible as absorption, and most clear around 20 minutes when the ribbon forms, and at roughly 28 minutes when a secondary ribbon appears.

The streak of positive values in the residual fits for the Ca II 8542 Å line at 8540.8 Å is due to a combination of unequal wavelength sampling and the drift of the FOV of the instrument over time, bringing more of the penumbra into view with time. This artifact would not be present in true Sun-as-a-star observations.

There is a blue-shifted absorption feature in the Ca II 8542 Å and H α line cores at times after $t \sim 60$ minutes. This is a result of taking the reference frames for the contrast profile around 55–60 minutes during the gradual phase of the flare. As the ribbon activity decreases slowly, the “contrast” therefore appears negative in the core at later times.

Event 8: An M1.9 flare on 2015 September 27

An M1.9 flare occurred in the active region NOAA 12423 on 2015-09-27 at ~10:40 UT. Approximately 10% of the flare ribbon area was captured in the FOV of the SST. The average μ value of the flare is 0.5. No CME is associated with the event. This flare was first described in Kuridze et al. (2018) and was observed during the IRIS and SST coordinated campaigns described in Rouppe van der Voort et al. (2020).

C1.9 and C2.4 Flare (2022-06-26)

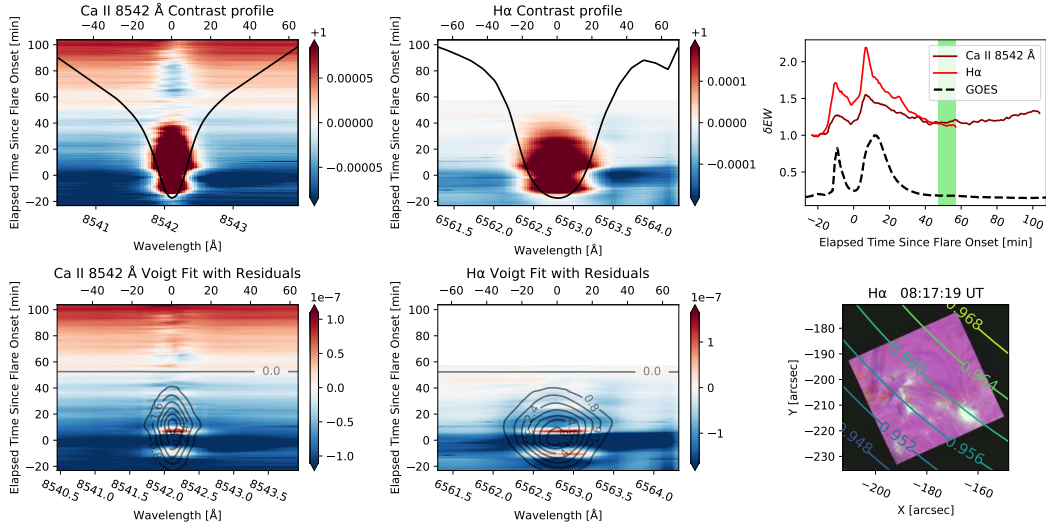


Fig. 17. Event 15. Same as Fig. 4 but for Ca II 8542 Å and Hα.

In this instance throughout the observations, there is an arcade of loops that overlaps the flare ribbon emission in the line of sight (Fig. 11, bottom right panel). From the line profiles and the cocoplot (particularly in Ca II 8542 Å), one can infer there is a transfer of relatively cool material along these arched fibrils occurring predominantly from one ribbon at $(X, Y) = (785'', -200'')$ toward the other ribbon at $(X, Y) = (780'', -225'')$ producing a net emission showing a blue Doppler shift in the line core.

As a result, the contrast profiles are strongly impacted throughout the duration of this action. The line core minimum position shifts left, to the shorter or bluer wavelengths. Therefore, relative to the reference spectrum, the emission in the wing wavelength left of the center appears lower, and that to the right appears greater. Additionally, the peak in the line δEWs is much later than the GOES peak in both cases. We believe that this is due to the cool material covering the flare ribbons.

When looking at a contrast profile or residual, a persistent net Doppler shift to one side generates a pair of enhanced and decreased emission on opposite side of the line core. Which side is enhanced and which decreased depends on whether the relevant material is behaving as an emission line (enhancement matches Doppler shift) or an absorption line (enhancement in opposite direction to Doppler shift). However, this signal is not associated with a related CME, despite exhibiting the CME spectral signature that stellar observers often look for (e.g., Namekata et al. 2021).

Event 9: An M1.8 flare on 2024 September 11

An M1.8 flare occurred in the active region NOAA 13814 on 2024-09-11 at ~12:27 UT. Approximately 80% of the flare ribbon area was captured in the FOV of the SST. The average μ value of the flare is 0.979. The event has an associated CME with 400 km s^{-1} . The analysis is displayed in Fig. 12.

This flare occurred in a very flare-productive region where it was the first of four M-class flares that day. Flare emission started at several locations almost simultaneously, shortly after a filament eruption that caused the associated CME. The flare consists of two main flare ribbons that merge with smaller flaring ribbons around them, much like Event 5. The grad-

ual phase is relatively short and thus the ribbon emission dies down relatively quickly. The repeated subsequent flares in the same location indicate that the reconnection in this flare only partially relaxed the surrounding magnetic topology, which could explain the relatively brief gradual phase of this flare.

This is the closest flare to the disk center. The filament and CME arose from material outside of the FOV. From the ribbons themselves we do not see much blue or red-shifted material from this flare, nor do we see any up- or down-flowing hot or cool overlying material in the videos, which also suggests that this is a rather confined event. Therefore, we highlight that the chromospheric lines do not evidence the associated CME via evaporation or condensation signatures.

Event 10: An M1.1 flare on 2014 September 6

An M1.1 flare occurred in the active region NOAA 12157 on 2014-09-06 at ~17:00 UT. Approximately 100% of the flare ribbon area was captured in the FOV of the SST. The average μ value of the flare is 0.56. No CME was associated with this event. This flare was first described in Kuridze et al. (2015) and was observed during the IRIS and SST coordinated campaigns described in Rouppe van der Voort et al. (2020).

This flare shows some striking differences to the M1.9 flare (Event 8). Both have similar strengths in GOES and occur near the limb. However, the emission from this flare is exceptionally symmetric in both the contrast profiles and the Voigt profile residuals (see Fig. 13). In this instance, no overlying absorbing material is present to provide absorption with a significant net Doppler shift, which results in the highly symmetric profiles. This emphasizes the power of coronal rain, filaments, and fibrils in determining the net Doppler velocities of Sun-as-a-star flare observations of chromospheric lines, especially when contrasted with the flare ribbons themselves. The same misinterpretation can also occur in spatially resolved studies, where individual wavelength images are inspected without appropriate context, showing what emission originates from flare ribbon and what spectral features are linked to overlying material. Context can easily be provided by a COCOPLOT.

C2.2 Flare (2023-06-18)

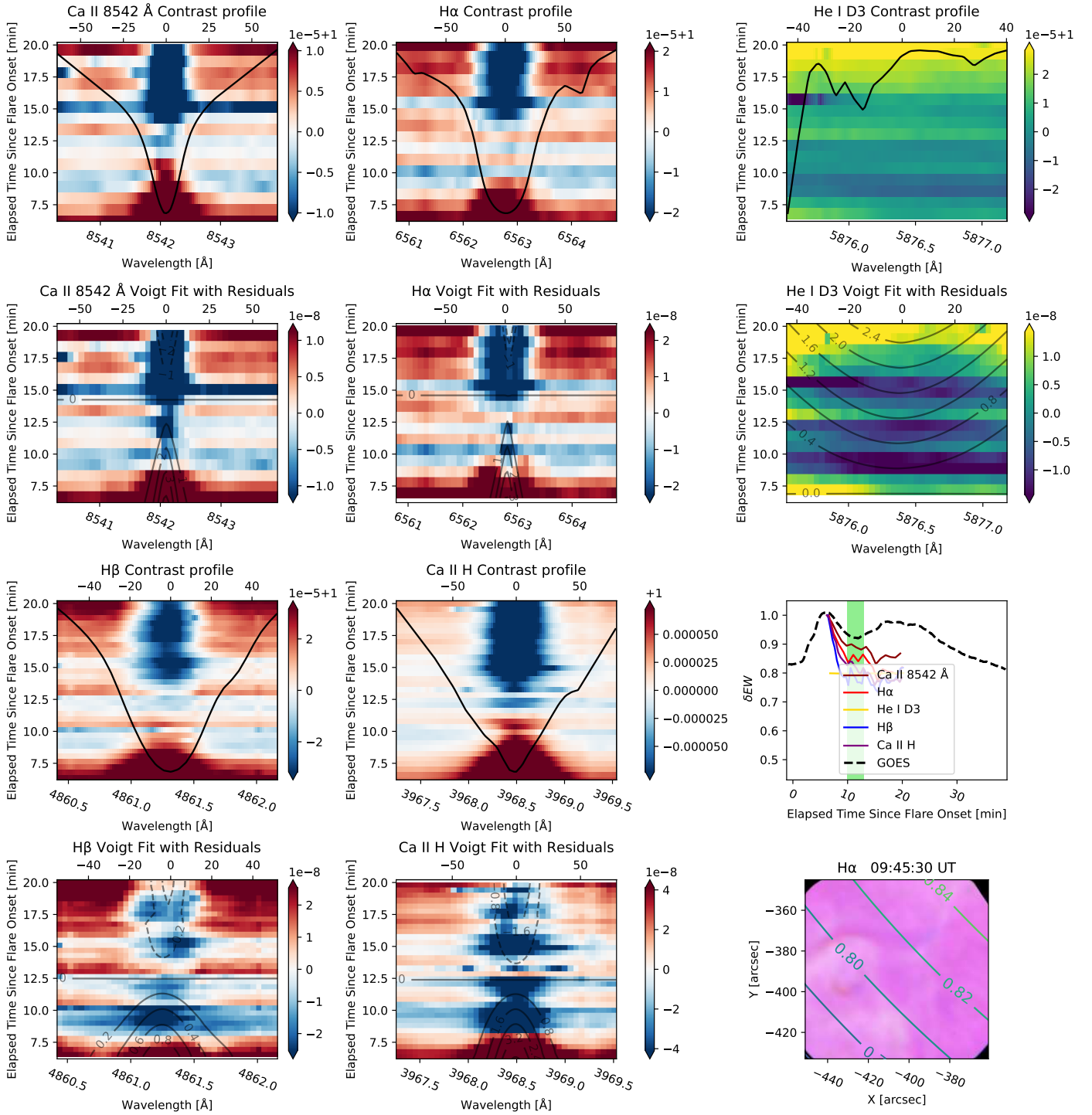


Fig. 18. Event 16. Same as Fig. 4 but for Ca II 8542 Å, Hα, He I D3, Hβ, and Ca II H. In the top right panel, the absorption features in the quiet-Sun profile (black curve) are blends of telluric H₂O and solar metallic lines (see Fig. 2 in Libbrecht et al. (2017) and the top panels of Fig. 4.4 in Libbrecht (2019)). Offset of δEW of He I D3 by 1.8.

Exceptionally, the observation includes a rather long segment of preflare data, which includes a detected microflare at ~60 minutes. We also observe a 50-minute line center darkening preceding the flare which then turns into faint red- and blue-shifted emission. The other investigated flares do not include long enough preflare data to check whether this is a common emission pattern, more pre-flare time series are needed to answer this question.

Event 11: A C8.4 flare on 2016 May 14

A C8.4 flare occurred in the active region NOAA 12543 on 2016-05-14 at ~11:28 UT at $\mu = 0.38$. The entirety (100%) of the ribbon area was captured in the FOV of the SST. A small 144 km s^{-1} CME was associated with this event. This flare was first described in Kuridze et al. (2017).

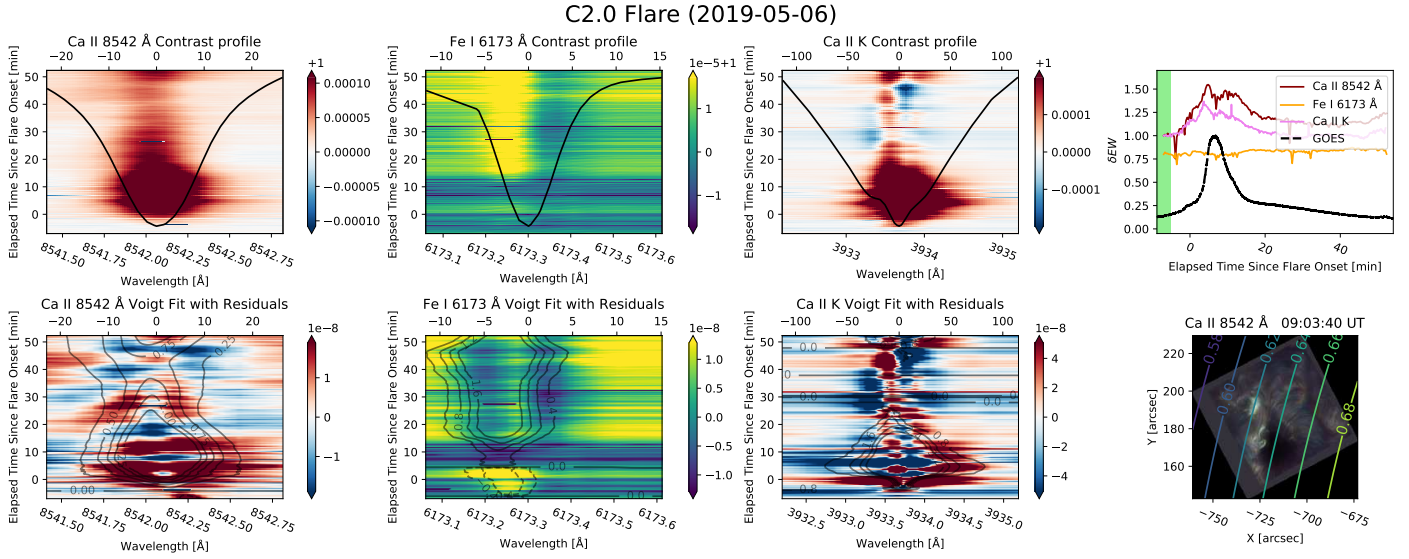


Fig. 19. Event 17. Same as Fig. 4 but for Ca II 8542 Å, Fe I 6173 Å, and Ca II K. Offset of δEW of Fe I 6173 Å by 1.8.

The impulsive phase of the flare started 5–10 minutes before the start of the SST observation (Fig. 14). A small filament/prominence was present over the classic sigmoid³ flaring area. The cool prominence material produces strong absorption in chromospheric lines where it covers the flaring area in the line of sight at times near the start of the SST observation. This is especially evident in H α observations where the prominence material is highly opaque (Fig. 14, bottom right panel, strong blue and red features). In the first ten minutes of the SST observation (flare time 10–20 minutes) the bright flare ribbon emission decreases, but there is also an evolution of the filament with up-and-downflows as well as the launch of some fraction as a CME. This reorganization and draining of the filaments clears the view of the flaring area leading to a clear second, more gradual “peak” in the flare emission (Fig. 14, top right panel) which is particularly strong in H α compared with Ca II 8542 Å, again due to the high opacity of the filament in H α .

The contrast profiles and Voigt residuals clearly show the effect of gravity acting on the overlying absorbing material in this filament from minutes 10–35 from the deceleration of upflowing material (blue wing absorption of the spectral lines in Fig. 14, left and central panels), and the acceleration of downflowing material (subsequent red wing absorption), which manifests in an approximately linear drift of the Doppler velocities to longer wavelength over time. Back-of-the-envelope calculations of the linear drift in Doppler velocity (–60 to 60 km s^{–1}) over a time of 25 minutes, viewed at angle $\mu = 0.38$ give a constant acceleration of 0.210 km s^{–2}. Given the errors in this calculation and the angle of the magnetic field with respect to the vertical, this action is consistent with draining under solar gravity (0.274 km s^{–2}). There is a blue-shifted absorption feature seen in the Ca II 8542 Å line core at times after $t \sim 50$ minutes. As in Event 7, this is a result of taking the reference frames for the contrast profile during the gradual phase of the flare.

Event 12: A C5.6 flare on 2015 June 24

An C5.6 flare occurred in the active region NOAA 12371 on 2015-06-24 at ~15:30 UT. Approximately 10% of the flare ribbon area was captured in the FOV of the SST from 5 minutes

³ Sigmoid flare ribbons are S-shaped, not σ shaped.

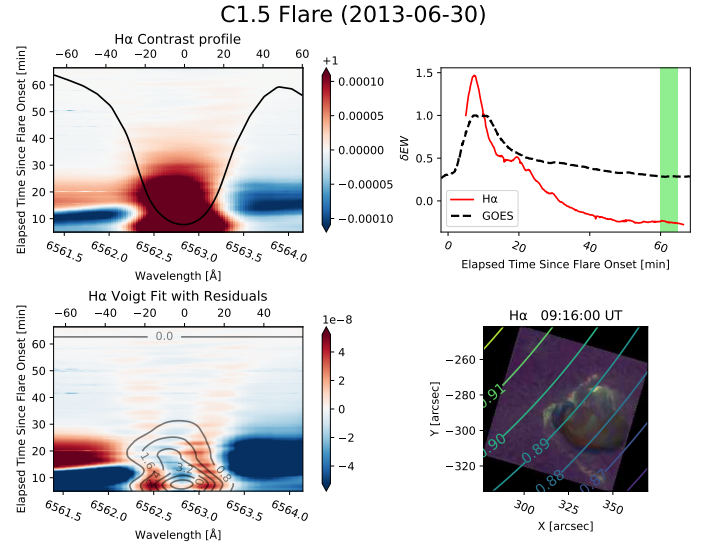


Fig. 20. Event 18. Same as Fig. 4 but for H α .

past the onset. The average μ value of the flare is 0.84. No CME is associated with this event. The analysis is displayed in Fig. 15.

This dataset changes its pointing around 30 minutes into the observation to better cover the flare. This causes a seeming discontinuity around the 10-minute mark. Hence, the normalization is taken after the readjustment. Several small jets and coronal rain can be seen throughout the FOV which manifest as red- and blue-shifted absorption around 60 minutes. The change in pointing at the time shortly before the GOES peak makes it difficult to strongly infer any delay in the timings of the peaks in emission of H α , Ca II 8542 Å, and GOES.

Event 13: A C4.1 flare on 2011 August 6

A C4.1 flare occurred in the active region NOAA 11267 on 2011-08-06 at ~08:40 UT. Approximately 50% of the flare ribbon area was captured in the FOV of the SST. The average μ value of the flare is 0.85. However, the only captured lines are Fe I 6302 Å and Fe I 5576 Å which are insensitive to flaring activity of this

C1.2 Flare (2021-05-26)

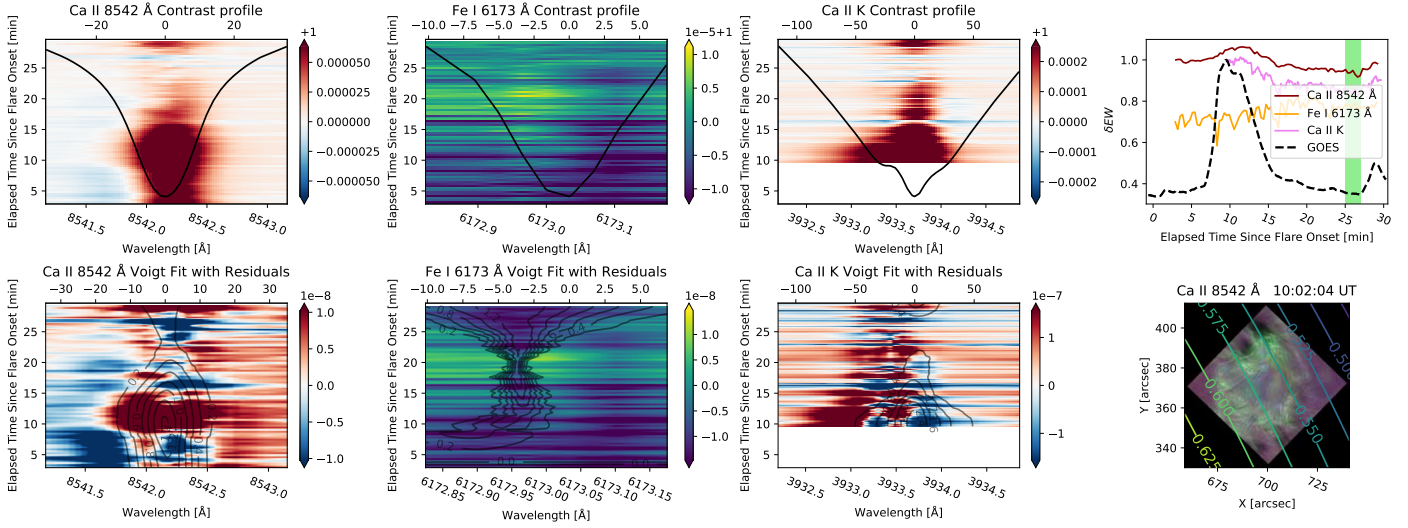


Fig. 21. Event 19. Same as Fig. 4 but for Ca II 8542 Å, Fe I 6173 Å, and Ca II K. Offset of δEW of Fe I 6173 Å by 1.7.

caliber. Therefore, this event was not pursued further. A detailed description of this event can be found in [Cristaldi et al. \(2014\)](#).

Event 14: A C3.6 flare on 2015 May 5

A C3.6 flare occurred in the active region NOAA 12335 on 2015-05-05 at ~11:55 UT ([Libbrecht et al. 2019](#)). Approximately 95% of the flare ribbon area was captured in the FOV of the SST, which observed only the He I D3 line. The average μ value of the flare is 0.929. No CME is associated with this event. This flare was first described in [Libbrecht et al. \(2019\)](#). The analysis is displayed in Fig. 16.

The observation starts with one bad frame as the telescope is still moving to capture the event (see Fig. 16).

In the contrast profile we can see some faint blueshifted emission, with a redshifted absorption next to it. The Voigt fit comes out negative due to a lack of emission core, and shows what seems to be a redshifted emission in the residuals, but this should in fact be interpreted as an absorption that slows down over time. Its presence aligns with the appearance and density of the flare feature seen in the data.

Event 15: A double C1.9 and C2.4 flare on 2022 June 26

A C1.9 flare followed by a C2.4 flare occurred in the active region NOAA 13040 on 2022-06-26 at ~08:12 UT. Approximately 90% of the second flare ribbon area was captured in the FOV of the SST. The average μ value of the flare is 0.959. No CME was associated with this event. A detailed description of this event can be found in [Thoen Faber et al. \(2025\)](#). The analysis is displayed in Fig. 17.

The first flare happens partially out of the field of view and produces associated cool coronal loop material that does not become a CME. Instead the material falls back down, obscuring some part of the flare ribbons and creating a dual blue- and redshifted absorption signatures. The second stronger flare starts toward the end of this process. From the pattern of the EWs alone it is not possible to tell whether this is one larger flare with emission that gets strongly absorbed near its start, or two smaller flares happening at relatively close times. In a true disk-integrated setting such an event could be mistaken for a single

stronger flare if no X-ray or white light information is available. In Ca II 8542 Å we see dimming in the contrast profile core wavelengths after the flare in a fashion similar to Event 7.

Event 16: A C2.2 flare on 2023 June 18

A C2.2 flare occurred in the active region NOAA 13336 on 2023-06-18 at ~09:31 UT. Approximately 100% of the flare ribbon area was captured in the FOV of the SST. The average μ value of the flare is 0.808. No CME was associated with this event. The analysis is displayed in Fig. 18.

This flare was once again captured several minutes after its onset, and thus the SST observations begin near the event peak. Note that the contrast is taken relative to a time during the flare, this confuses interpreting the contrast profiles and Voigt fit residuals. All lines initially show a very similar pattern with a central brightening. After minute 10, a naive interpretation would be of a central dimming, which starts at minute 14 and continues throughout the rest of the time series, which is comparatively very short. However, in reality this represents a gradual dimming of the core enhancement which has its peak near the start of the flare. The horizontal “bands” visible in the contrast profiles and Voigt fits are due to variable seeing conditions.

We see dimming in the contrast profile core wavelengths later in the flare in a fashion similar to Event 7 due to taking the reference profile at 10–15 minutes.

Event 17: A C2.0 flare on 2019 May 6

A C2.0 flare occurred in the active region NOAA 12740 on 2019-05-06 at ~08:45 UT. Approximately 100% of the flare ribbon area was captured in the FOV of the SST. However, this alters through time and there is substantial in and outflow in the FOV by the rotational nature of the flare. The average μ value of the flare is 0.64. A weak 128 km s^{-1} CME is associated with this event. The flare was first described in [Yadav et al. \(2021\)](#). The analysis is displayed in Fig. 19.

To better capture the event, the FOV was moved two times during this time series, causing jumps in the contrast profiles. These jumps took place around 5 and 32 minutes and caused some visible distortions in the profiles. Besides this, we can see

the characteristic red-shifted emission caused by the flare ribbon formation processes compacting pre-existing chromosphere structures (as in Event 7). Any effects due to blue or redshifted cool overlying material later on in the time series are difficult to discern due to the impact on the net emission of the shift in telescope pointing.

Event 18: A C1.5 flare on 2013 June 30

A C1.5 flare occurred in the active region NOAA 11778 on 2013-06-30 at ~09:20 UT, associated with a confined filament eruption (Doyle et al. 2019) but no CME. Full capture of the flare ribbon area in the FOV of the SST is assumed. The average μ value of the flare is 0.64. This flare was first described in Druett et al. (2017). The analysis is displayed in Fig. 20.

This flare is covered by the aforementioned filament eruption which launches a large amount of material up toward the observer, leaving a strong blue-shifted excess absorption signature near the start of the observation. Around 15 minutes into the event, a significant fraction of this overlying material falls back down as coronal rain, which is clearly seen via absorption in the red wing of the contrast profiles. The flare ribbon emission below becomes more visible with time due to the decreasing overlap with overlying material. This reveals some red-shifted emission due to flare ribbon formation as in Event 7. Each of these physical processes is clearly and simply manifested in the contrast profiles, partially aided by a long observation sequence that provides a suitable stable reference profile to help construct easily interpretable contrast profiles. However, the previously described flare events illustrate that such a clear correspondence between spectral signature and physical motions does not always hold true.

The oscillations in intensity are once again seeing induced.

Event 19: A C1.2 flare on 2021 May 26

A C1.2 flare occurred in the active region NOAA 12826 on 2021-05-26 at ~09:55 UT. Approximately 100% of the flare ribbon area was captured in the FOV of the SST. The average μ value of the flare is 0.56. No CME is associated with the event. The analysis is shown in Fig. 21.

This event represents a particularly weak flare inside of a decaying active region that produced several more C-class flares in the following days before it rotated out of sight behind the limb. In this case, one primarily sees mildly tangled field lines linking the fragmented spots and pores of the decaying region. The flare occurs at the light bridge in the upper corner of the observation and starts off very delicately with several small micro-flare brightenings before a larger reconnection occurs around 7 minutes. Around 15 minutes the reconnection calms down before several new microflares occur around 20 minutes and toward the end of the time series.

The seeming blueshift visible in the iron line seems to be primarily caused by changes in the FOV pointing during the time series, as it slowly rotates in a way that increases the amount of penumbra on one side of the FOV, while cutting it off on the other.

3.3. Flare energy scaling law

The quantitative results presented in the previous section motivated us to explore a possible correlation between the peak values of contrast profiles and the radiated bolometric flare energy (hereafter the flare energy). We assumed a linear relationship

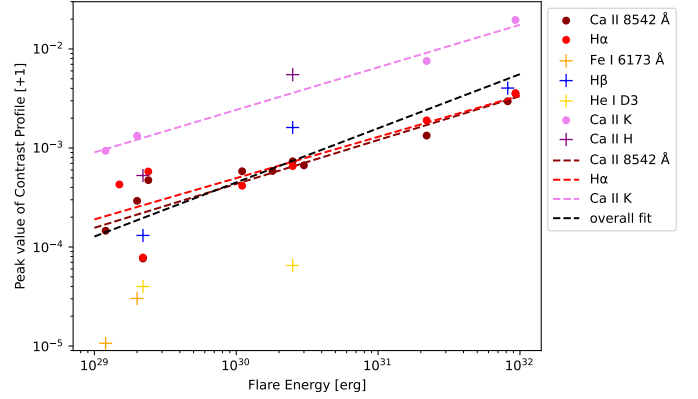


Fig. 22. Correlation between peak values of contrast profiles and flare energy. Lines with four or more data points were fitted individually, while lines with fewer were only considered for the overall fit. Lines with individual fits are Ca II 8542 Å, Hα, Ca II K lines (dots) and lines only considered for the overall fit are Fe I 6173 Å, He I D3, Hβ, Ca II H lines (plus signs).

Table 1. Correlation coefficients (R) and fitting parameters for the function $\log_{10}(C_{\text{peak}}) = b + a \log_{10}(E)$ corresponding to the data in Fig. 22.

Line	R	b	a
Ca II K	0.995	-35.7	0.430
Ca II 8542 Å	0.924	-38.3	0.443
Hα	0.847	-36.4	0.417
Overall Fit	0.744	-45.5	0.547

between energy and soft X-ray flux in the 1–8 Å passband, as measured by GOES, setting an X1.0 flare to 10^{31} erg (e.g., Fig. 2 in Shibata et al. (2013) and Fig. 5 in Maehara et al. (2015)). Fig. 22 illustrates the correlation between the peak values of contrast profiles, C_{peak} , and flare energy, E . The C_{peak} values for spectral lines with four or more measurements (i.e., Ca II 8542 Å, Hα, and Ca II K) are represented by dots, while those with fewer than four measurements (Fe I 6173 Å, He I D3, Hβ, and Ca II H) are shown as plus signs. Events 4, 11, and 14 are excluded as we cannot confirm that the observations captured the peak in δEW . Events 5, 8, and 12 exhibit less than 30% overlap between the FOV and the flare and are therefore excluded, as scaling the intensity by the inverse of the overlap (O^{-1} in Eq. (2)) introduces large errors. Fig. 22 suggests a power-law relationship of the form $C_{\text{peak}} \sim E^a$, which can be expressed as $\log_{10} C_{\text{peak}} \sim a \log_{10} E$. The corresponding linear fits for the values C_{peak} with four or more measurements are depicted by dashed lines, with colors that match the respective spectral lines. The overall fit, which incorporates all values of C_{peak} , is shown as a black dashed line. Correlation coefficients and fitting parameters are listed in Table 1. The slope values a suggest that the peak values of contrast profiles approximately scale as the square root of flare energy.

4. Conclusions

In this work, we have used a unique collection of 20 solar flares observed with the SST (see Fig. 2) to obtain statistically relevant results. These limited-FOV time series were averaged and turned into approximations of disk-integrated spectra using the NESSI code (Pietrow & Pastor Yabar 2024) which

were shown to closely reproduce true Sun-as-a-star observations with certain caveats such as the incomplete capture of a flare, seeing variations, as well as FOV shifts, jumps and drifts. As noted, limited-FOV observations are prone to errors introduced by quiet-Sun areas adjoining sunspots or active regions. Our method mitigates these issues while exploiting the main advantage of a restricted FOV—namely, isolating the spectral influence of the flaring region itself. Partially covered flares therefore remain informative, because the behavior they reveal still contributes to the flare’s overall spectral evolution; however, caution is warranted, as unobserved portions of the event may introduce unaccounted-for effects.

While only the strongest events from our sample have enough S/N to show up in true Sun-as-a-star and stellar observations, we believe that there is still merit in observing weaker events as their higher occurrence rate allows for better statistics, especially since these are physically the same events.

Overall we note that the imprint of flares on the Sun-as-a-star spectrum is strongest in the Ca II H & K lines, which is in line with the findings of Pietrow et al. (2024a). This means that these lines are crucial for identifying activity that may not be as clearly present in other lines.

The analysis of contrast and residual profiles across a broad sample of flares reveals several recurring spectral features. The most prevalent is core intensity enhancement (Feature 1), or absorption in the case of He I D₃, associated with the flare peak. Its presence is typically accompanied by line broadening and an enhancement in the normalized differenced equivalent width (δEW). A second frequent feature is transient redshifted emission (Feature 2), attributed to down-flowing plasma, likely coronal rain, in flare loops, most clearly detected at viewing angles that maximize the line-of-sight velocity component. Filament and flare loop imprints (Feature 3) manifest in a subset of events as dynamic reversals in wing asymmetry, driven by evolving structures obscuring the flare ribbons. Finally, several events show a temporal offset between δEW and GOES peak times (Feature 4), suggesting variability in the timing of chromospheric response relative to coronal emission; however, incomplete temporal coverage in some cases limits definitive conclusions.

Of the sampled flares, 53% had cataloged CMEs, yet only one (Event 11) showed distinct spectral signatures resembling known CME-associated profiles—highlighting the lack of a consistent spectral fingerprint for CME detection. Several non-CME events exhibited CME-like Doppler features caused by gravitationally bound upflows, emphasizing the risk of false positives. These findings underscore the limitations of using flare presence or Doppler signatures alone to infer CMEs and call for further research to improve the reliability of stellar CME diagnostics.

Pseudo Sun-as-a-star analysis of flares has so far mainly been focused on individual cases (Namekata et al. 2022; Xu et al. 2022; Otsu et al. 2024; Otsu & Asai 2024), with the exception of Otsu et al. (2022) who studied seven events, and Yu et al. (2025) who took a more general simulated approach. We believe that our work represents a large step in this field, due to the number of studied events that make it possible for statistically significant commonalities to be found, although we believe that even larger studies are necessary. Our simulated full-disk observations using the NESSI code also allowed us to have accurate intensities for the contrast profiles and residuals, which have often been lacking in previous works.

Additionally, this work allowed us to validate these previous studies, as our flares are observed at a much higher spatial and temporal resolution. Perhaps unsurprisingly, we do not report a

strong gain from the resolution increase, but we could temporally resolve much more of the flare structure. Additionally, the multi-line observations used in this work provided additional information that is often missing from single-line observations.

We believe that the spectral features described in this paper can help interpret unresolved stellar flares, as well as show that strong blue-shifted absorption does not necessarily indicate a CME. However, we also urge for more studies of this type with larger amounts samples of flares to help solidify these findings.

Data availability

The datasets in this work are collected from a large number of observers and institutes, with only some of them being public. Please contact the corresponding author for more information on specific sets.

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Appendix A: Event table

Table A.1. Event List

No.	Date ^a	NOAA ^b	Class ^b	V_{CME}^c (km s ⁻¹)	Flare Start/Peak/Stop ^b (UT)	SST Start/Stop (UT)	Overlap ^d	(X, Y) ^e ($''$)	μ	Lines	Cad. (s)
1	2017-09-06	12673	X9.3	1571	11:53/12:02/12:10	11:56/12:52	~ 40%	(513, -216)	0.815	Ca II 8542 Å H α Ca II K	15.0 15.0 6.6
2	2017-09-10	12673	X8.2	3163	15:35/16:06/16:31	16:23/18:32 16:23/18:32 16:25/17:49 16:25/17:49	~ 50%	(959, -144)	0.124	Ca II 8542 Å Fe I 6302 Å H β Ca II H & K	46.1 46.1 21.5 19.7
3	2017-09-06	12673	X2.2	391	08:57/09:10/09:17	09:04/09:54	~ 50%	(542, -208)	0.803	Ca II 8542 Å H α Ca II K	15.0 15.0 6.6
4	2014-06-10	12087	X1.5	925	12:36/12:52/13:03	12:40/12:58	~ 75%	(-879, -305)	0.139	H α	4.0
5 [†]	2021-10-28	12887	X1.0	1519	15:17/15:35/15:48	15:32/16:08	~ 10%	(150, -550)	0.804	Ca II 8542 Å Fe I 6173 Å	21.6 21.6
6 [†]	2022-05-20	13014	M3.0	–	07:35/07:45/07:49	07:45/08:41	~ 90%	(-11, 358)	0.927	Ca II 8542 Å Ca II 8542 Å H α	21.5 53.7 53.7
7 [†]	2023-06-09	13331	M2.5	651	16:48/17:11/17:34	17:01/17:52	~ 40%	(-598, -353)	0.688	He I D3 H β Ca II H	53.7 25.0 25.0
8	2015-09-27	12423	M1.9	–	10:20/10:40/10:46	10:35/10:59	~ 10%	(775, -233)	0.502	Ca II 8542 Å H α	32.3 32.3
9	2024-09-11	13814	M1.8	400	12:27/12:36/12:47	12:31/13:22	~ 80%	(146, 130)	0.979	Ca II 8542 Å	35.7
10 [‡]	2014-09-06	12157	M1.1	340	16:50/17:09/17:22	15:27/17:27	~ 100%	(-732, -302)	0.560	Ca II 8542 Å H α	11.6 11.6
11	2016-05-14	12543	C8.4	144	11:28/11:34/11:37	11:38/12:50	~ 100%	(877, -66)	0.384	Ca II 8542 Å H α	12.4 12.4
12 [‡]	2015-06-24	12371	C5.6	–	15:12/15:29/15:40	14:49/16:45	~ 10%	(496, 175)	0.841	Ca II 8542 Å H α	13.7 13.7
13 [‡]	2011-08-06	11267	C4.1	–	08:37/08:47/08:51	09:00/09:37	~ 50%	(-359, -359)	0.848	Fe I 6302 Å Fe I 5576 Å	28.3 28.3
14 [†]	2015-05-05	12335	C3.6	–	11:55/11:58/12:00	11:57/12:01	~ 95%	(-300, -190)	0.929	He I D3	14.9
15	2022-06-26	13040	C1.9 +C2.4	–	07:44/07:50/07:55 08:00/08:12/08:20	07:37/08:44 07:37/08:57	~ 90%	(-135, -235)	0.959	Ca II 8542 Å H α	40.3 40.3
16 [†]	2023-06-18	13336	C2.2	–	09:31/09:37/10:09	09:37/09:52	~ 100%	(-407, -390)	0.808	Ca II 8542 Å H α He I D3 H β Ca II H	53.6 53.6 53.6 25.0 25.0
17	2019-05-06	12740	C2.0	128	08:41/08:47/08:51	08:34/09:33	~ 100%	(-717, 186)	0.638	Ca II 8542 Å Fe I 6173 Å Ca II K	20.9 20.9 7.8
18	2013-06-30	11778	C1.5	–	09:11/09:18/09:27	09:16/10:17 09:49/10:16	100%	(323, -288)	0.892	H α Ca II 8542 Å	7.3 19.2
19 [†]	2021-05-26	12826	C1.2	–	09:46/09:55/10:00	09:49/10:16 09:55/10:16	~ 100%	(700, 350)	0.564	Fe I 6173 Å Ca II K	19.2 7.3

Notes. ^(†) The data are archived in [the Stockholm SST Archive](#). ^(‡) The data are archived in [the QUB Solar flare database](#). ^(a) YYYY-MM-DD. ^(b) From [SolarSoft Latest Events Archive](#). ^(c) Linear Fit Speed from the [SoHO/LASCO CME Catalog](#) (Gopalswamy et al. 2009). ^(d) Spatial overlap primarily estimated between the CRISP FOV and the total flare area in AIA 1700. ^(e) The coordinates represent the average estimated center of the flare within the CRISP and/or CHROMIS FOV, determined by excluding highly variable regions and focusing on consistently covered areas.