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Indications of stellar coronal mass ejections through coronal dimmings

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Coronal mass ejections (CMEs) are huge expulsions of magnetized matter from the Sun and stars, traversing space with speeds of millions of kilometres per hour. Solar CMEs can cause severe space weather disturbances and consumer power outages on Earth, whereas stellar CMEs may even pose a hazard to the habitability of exoplanets. Although CMEs ejected by our Sun can be directly imaged by white-light coronagraphs, for stars this is not possible. So far, only a few candidates for stellar CME detections have been reported. Here we demonstrate a different approach that is based on sudden dimmings in the extreme ultraviolet and X-ray emission caused by the CME mass loss. We report dimming detections associated with flares on cool stars, indicative of stellar CMEs, and which are benchmarked by Sun-as-a-star extreme ultraviolet measurements. This study paves the way for comprehensive detections and characterizations of CMEs on stars, which are important factors in planetary habitability and stellar evolution.

oronal mass ejections (CMEs) expelled from the Sun to interplanetary space are frequently observed, with occurrence rates of about five per day during solar maximum and one per day during solar minimum periods. Fast CMEs are generally associated with flares; that is, sudden outbursts of radiation. Flares and CMEs are different facets of a joint underlying physical process that involves instabilities and reconnection of magnetic fields in active regions^{1,2}. Late-type stars have outer convection zones and therefore exhibit stellar activity and maintain coronae similar to that of our Sun. They produce flares that can be orders of magnitude more energetic than solar flares³. Stellar flares are common and are observed at soft X-ray and optical wavelengths, in particular^{4,5}. The situation is very different for the observations of stellar CMEs. In the case of the Sun, CMEs can be directly imaged by coronagraph instruments that block the million-times-brighter radiation from the Sun's surface, and their speeds and masses can be derived. This is not possible for stellar CMEs. However, stellar CMEs and flares have recently gained increased attention, due to their potential impact on stellar evolution^{3,6} and the habitability of exoplanets^{7,8}. Further relevance is given by the recently detected 'superflares' on solar-like stars⁹, and their implications for the most disastrous space weather events our Sun might produce.

Different approaches have been explored in attempts to observe signatures of stellar CMEs. So far, the most promising one is the Doppler signal produced by CME-related plasma motions detected on a few main- and pre-main-sequence M stars in optical^{10–15} and ultraviolet spectra^{16,17}, as well as one X-ray detection on a giant star¹⁸. Searches for type II radio bursts generated by shock fronts driven by fast CMEs have not yet succeeded^{19,20}. Indirect CME signatures have been reported in the form of increased X-ray column densities and transient ultraviolet absorptions during flares^{21–23}. In total, there are fewer than 20 reported stellar CME detections, and they are not unambiguous^{18,24,25}. Here, we present a different and more direct approach, the study of sudden decreases of the extreme

ultraviolet (EUV) and X-ray emission from solar and stellar coronae due to the matter ejected by CMEs, so-called coronal dimmings.

Coronal dimmings caused by CMEs have been regularly observed on the Sun for more than 20 years at EUV and soft X-ray wavelengths²⁶⁻²⁸. They are observed over a broad range of coronal temperatures, but show up most prominently for the 1-2 million Kelvin plasma of the quiet corona^{29,30}. Dimming regions map to the bipolar ends of closed magnetic field lines that become stretched or temporarily opened during an eruption, and they are a result of the depletion of coronal plasma caused by the expansion and mass loss due to the CME^{26,27}. Recently available multi-point imagery from satellites at different locations in the heliosphere provided us with unprecedented 'quadrature' observations of the three-dimensional evolution of solar CMEs and their associated coronal dimmings. For a unique set of 62 events, coronal dimmings were observed on-disk by the Atmospheric Imaging Assembly (AIA)³¹ on board the Solar Dynamics Observatory (SDO), while the CMEs causing them were observed close to the solar limb by the Solar Terrestrial Relations Observatory (STEREO)³², minimizing projection effects in the determination of CME speeds and masses^{30,33}. These studies showed that in narrowband EUV imagery, the spatially resolved dimming regions reveal emission decreases of up to 70% (ref. ³⁰). The CME mass and speed were found to be correlated with key parameters of the associated coronal dimmings such as the spatial extent and intensity drop^{33,34}. Notably, CME-associated dimmings have been also identified in various ionization stages of iron lines (FeIX to FeXIV) in full-Sun EUV irradiance measurements^{35–37}.

Here, we evaluate Sun-as-a-star EUV irradiance measurements by the Extreme ultraviolet Variability Experiment (EVE)³⁸ on board SDO as a testbed to study whether coronal dimmings can be also observed on stars and used for stellar CME detection. To this aim, we derive broadband Sun-as-a-star EUV light curves from the SDO-EVE spectra for a set of large flares, analyse these light curves for the occurrence of significant coronal

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NATURE ASTRONOMY



Fig. 1 | **Coronal dimming event on Sun on 2012 March 7. a,b**, SDO-AIA 19.3 nm direct (**a**) and logarithmic base-ratio (**b**) images showing the flare and coronal dimming. The red box in **a** marks the region that was used to calculate the flare light curve shown in **d** (top). The black arrows indicate the dimming regions. The colour bar above **b** marks the logarithmic values (dimensionless) that are indicative of the changes with respect to the pre-event emission for the images shown in **b**. **c**, The CMEs imaged by the STEREO-B Extreme Ultraviolet Imager and COR2 white-light coronagraph. The red contours outline the CME fronts. **d**, Top: spatially resolved SDO-AIA 19.3 nm light curves of the flare (red curve) and dimming region (blue curve), from which pre-event emission is subtracted. Middle: SDO-EVE 15-25 nm broadband Sun-as-a-Star light curve. The horizontal dashed line indicates 0% relative difference. Bottom: pre-event subtracted SDO-EVE irradiance spectra. The spectra are integrated over 10 min during the flare peak (red; the plotted vertical range is cut) and over the maximum dimming depth (blue), as indicated by orange and blue vertical lines and shaded regions in the middle panel. Supplementary Video 1 is available with this figure.

dimmings, and evaluate the association between coronal dimmings and CMEs (see 'SDO-EVE Sun-as-a-star solar dimming identification and CME association' in the Methods). This thorough approach allows us to quantify (1) how frequently coronal dimmings are observed in Sun-as-a-star EUV light curves as a signature of the accompanying CME, (2) how robust the CME detection via dimmings is against false alerts, and (3) how well coronal dimmings serve as a proxy for CMEs. The dataset consists of 44 large flares (Geostationary Operational Environmental Satellite (GOES) class \geq M5) observed in SDO-EVE irradiance spectra. The events have been classified in previous studies^{37,39} as eruptive (that is, associated with a CME: 38) and confined (that is, without an accompanying CME: 6) flares. Table 1 shows the contingency table for the CME and dimming occurrences, from which we infer a high conditional probability for the occurrence of a CME given that a coronal dimming was observed in the 15-25 nm broadband SDO-EVE light curve in the aftermath of a large flare, P(CME | Dim) = 0.970. In addition, we infer from Table 1 that coronal dimmings are a frequent phenomenon associated with CMEs, P(Dim | CME) = 0.842, whereas the probability of false alerts is small, P(Dim | !CME) = 0.167. These findings demonstrate that coronal dimmings caused by CMEs have been

Table 1 | The occurrence of CMEs and coronal dimmings in association with large flares, as derived from SDO-EVE 15-25 nm broadband light curves and full-disk integrated SDO-AIA 19.3 nm light curves

EVE		!Dimming	Dimming
	!CME	5	1
	CME	6	32
AIA			
	!CME	14	2
	CME	13	39

identified in spatially unresolved broadband EUV data, with the emission dropping by 0.4–5.5% relative to the pre-event level (Supplementary Table 1).

To increase statistics, the analysis has been expanded by integrating the spatially resolved emission from SDO–AIA 19.3 nm full-disk images to create full-Sun light curves for a larger set of 68 flares (52 eruptive, 16 confined)^{37,39}. The probabilities derived from this



Fig. 2 | Coronal dimmings on Proxima Centauri. a-h, Two dimming events on Proxima Centauri. Background-subtracted XMM-Newton X-ray (0.2-2 keV) light curves (**a**,**c**). The weighted spline fits (blue) to the PN (**a**) and MOS1 (**c**) data, as well as the adopted quiet levels (red dashed lines) are shown. Dimming and quiet intervals are highlighted by blue and grey shaded areas, respectively. Simultaneous photometric fast mode observations with XMM-Newton's Optical/UV Monitor Telescope in the U band (**b**,**d**). PN (**e**) and MOS1 (**g**) spectra in the energy range 0.2-2 keV for different time intervals. The time intervals are quiet phase (Q), flare 1 (F1), dimming phase (D), flare 2 (F2) and flare 3 (F3). Total emission measure (EM) and emission-measure-weighted temperature from spectral fitting (**f**,**h**). The time intervals are indicated by vertical lines, and the light curves (arbitrarily scaled) are shown in grey. Vertical error bars are 1 σ uncertainties. Horizontal bars indicate the extent of the energy (**e**,**g**) and time bins (**f**,**h**), respectively.



Fig. 3 | Coronal dimming on AB Dor. Background-subtracted EUVE Deep Survey (DS) telescope (8–18 nm) light curve with data binned to 5,620 s, corresponding to one EUVE orbit. Error bars are 1σ uncertainties. The blue line shows the weighted cubic-spline fit. Grey shaded areas denote periods used to determine the quiescent level (red dotted line). The light-blue shaded area marks the dimming.

extended dataset give a consistent picture with those derived from SDO-EVE, with P(CME | Dim) = 0.951, P(Dim | CME) = 0.750 and P(Dim | !CME) = 0.125. Note that in the subsample that overlaps with SDO-EVE, for 42 out of 44 events, the EVE and AIA dimming identifications agree. These findings provide strong evidence that dimmings are a good and robust proxy for CMEs, because (1) the coronal dimmings identified in the EUV light curves are with very high probability due to a CME accompanying the flare, and (2) CMEs associated with large flares frequently manifest themselves as significant coronal dimmings in Sun-as-a-star EUV light curves. Under the plausible assumption that the coronal environment in other late-type stars behaves in a similar way to our Sun, coronal dimmings are an excellent means for stellar CME detection.

Figure 1 and Supplementary Video 1 demonstrate for the 2012 March 7 event the relation between the spatially resolved dimming observed by SDO–AIA and the unresolved Sun-as-a-star observations by SDO–EVE, together with its CME. This event reveals the strongest EVE dimming, and it is caused by a very fast and massive CME (maximum speed $3,700 \,\mathrm{km}\,\mathrm{s}^{-1}$ and mass $1.8 \times 10^{16}\,\mathrm{g}$) (ref. ³³), followed by another fast CME that originated in the same active region within 1 hour. AIA 19.3 nm images (Fig. 1a) show the bright solar flare as well as localized dark dimming regions on both ends of the flare arcade. Corresponding base-ratio images (Fig. 1b), in which each frame was divided by a pre-event image to enhance the changing features, reveal the global nature of the dimming. Figure 1c shows the double CME that caused this dimming, as observed by the Extreme Ultraviolet Imager and white-light coronagraph COR2 (ref. ³²) on board STEREO-B located 118° east of Earth.

The relation between spatially resolved and unresolved EUV light curves, which is key to make the transition to the stellar case, is also shown in Fig. 1. To understand the interplay of two competing effects in the spatially unresolved SDO–EVE light curves, which are the emission enhancement due to the flare and the decrease due to the dimming, we use SDO–AIA imagery to derive light curves separately for the flare and the dimming regions. The flare emission increase and the dimming emission decrease start roughly simultaneously, which can be understood in terms of the coupling of the CME dynamics and the flare energy release by magnetic reconnection in the large-scale current sheet beneath the erupting structure^{1,2}. However, the dimming continues much longer, which enables its detection in the unresolved data. The flare duration is

NATURE ASTRONOMY

related to the energy release and cooling time scales of the hot flaring plasma, whereas the dimming duration is related to the time scales for replenishment of the solar corona in the aftermath of a CME and the related mass loss. The evolution of the segmented components is reflected in the SDO–EVE 15–25 nm Sun-as-a-star light curves, which are initially dominated by the strong flare enhancement but then show an emission decrease due to the dimming after about 110 min. Two SDO–EVE spectra that are subtracted by a pre-event spectrum are shown in Fig. 1: the red one is centred at the peak of the flare, and the blue one is at the maximum depth of the dimming. The spectra show strongly enhanced flare continuum and spectral lines, whereas the dimming is dominated by spectral lines that are most prominent in the wavelength range 17–21 nm.

In Extended Data Fig. 1, we show broadband EUV and X-ray full-Sun light curves of five more examples of CME-associated flares to illustrate various dimming cases: a dimming that is interrupted by a subsequent large flare, an impulsive flare after which the dimming shows up promptly, a long-duration flare followed by a very weak, but significant, dimming, a very gradual dimming, and a strong dimming that remains at deep level for >11 h. Extended Data Fig. 2 shows, for comparison, an example of a confined flare with no dimming and the only confined flare for which a significant EVE dimming was identified, which was much weaker and less impulsive than most of the dimmings associated with eruptions.

As we have shown that coronal dimmings are detectable in broadband Sun-as-a-star EUV light curves and that there is a high conditional probability that the occurrence of a dimming event associated with a large flare is accompanied by a CME, P(CME | Dim) = 0.97, we can apply these important findings to the stellar case. We focus on Sun-like and late-type (F, G, K and M) main-sequence and pre-main-sequence stars. Coronal temperatures of active Sun-like stars are correlated with their X-ray emission⁴⁰, and more active stars may reveal higher coronal temperatures than the Sun⁴¹. This implies that stellar dimmings may be also observable at shorter wavelengths. Therefore, we explored data archives of missions operating at EUV wavelengths, such as the Extreme Ultra-Violet Explorer (EUVE, ref. 42, 7-76 nm) launched by NASA (the National Aeronautics and Space Administration), as well as at soft X-ray wavelengths, such as the European Space Agency's X-ray Multi-Mirror Mission (XMM-Newton, ref. 43, 0.1-6 nm) and NASA's Chandra X-ray Observatory (ref. 44, ~0.1-20.7 nm). We compiled observations from 201 stars (see 'Sample selection of solar-like and late-type flaring stars' in the Methods). In order to identify flares, we constructed light curves that cover also the pre- and post-flare phases. These were subsequently analysed for flare-associated dimmings indicative of stellar CMEs, and we applied the following criteria: (1) after the flare, the EUV or X-ray flux drops significantly (> 2σ) below the quiescent pre-flare level in at least one energy band, and (2) after reaching a minimum, the flux increases again towards the pre-flare level (see 'Light-curve binning' and 'Determination of stellar dimming parameters and significance' in the Methods). This analysis yielded 21 dimmings detected on 13 different stars, 1 from EUVE, 3 from Chandra and 17 from XMM-Newton (Supplementary Table 2). Notably, about half of the events were found on three stars: the young and rapidly rotating K0V star AB Dor (five events), the young M0Ve star AU Mic (three events) and the nearby M5.5Ve star Proxima Centauri (two events). The other events were found on G- to M-type pre-main-sequence and main-sequence stars.

Two dimming events detected on Proxima Centauri are shown in Fig. 2. The XMM-Newton 0.2–2 keV light curve shows that the dimming starts immediately after a small, short flare, and reaches a maximum depth of 36% and lasts for approximately three hours before it is interrupted by three subsequent flares. During the indicated dimming interval, one small flare occurs also. A small flare followed by a pronounced dimming with a decrease of 56% and



Fig. 4 | Characteristics of solar and stellar dimmings. a-I, Distributions of dimming parameters derived from the solar (left) and stellar (right) samples, with mean μ and standard deviation σ values annotated. Parameters shown include dimming depth (**a**,**g**), duration (**b**,**h**), rise time (**c**,**i**), recovery time (**d**,**j**), delay between flare peak and dimming start (**f**,**l**). Red-coloured dimming duration and recovery times indicate solar events where the dimming end was not reached within the 12 h observation interval.

a duration of 4.5 h (again interrupted by subsequent flares) is also shown in Fig. 2. All flares are also seen in the photometric U band, revealing a very stable flux level outside flaring periods. Spectra, as well as temperature and emission-measure evolution derived from spectral fits are also shown (Fig. 2). They reveal a strong emission measure drop during the dimming, which provides further support

for the supposition that the stellar dimmings are due to coronal mass loss.

The only dimming event detected with EUVE in its Deep Survey telescope data (8-18 nm) is shown in Fig. 3 for the star AB Dor. The light curve shows five flares. After the last one at 93.7 h, the count rate drops below the quiescent level by 34%, followed by a gradual recovery, with a total dimming duration of 11.4 h. The data shown cover roughly nine rotations of AB Dor. They reveal a stable quiescent level and no obvious rotational modulation⁴⁵. In total, we identified five dimming events on AB Dor (one in EUVE, four in XMM-Newton data; Extended Data Figs. 3 and 4). An important issue for dimmings that occur on rapidly rotating stars is the maximum observability of the source region. If the star has an inclination $i = 90^{\circ}$, an active region can be generally detected for half of a stellar rotation period until it rotates off of the disk. AB Dor has $i=60^{\circ}$ (ref. ⁴⁶), which means we can see the star's pole. Doppler imaging has revealed a large polar starspot on AB Dor (refs. 47,48). The duration from flare peak to dimming end is 13.3h (Fig. 3), which is more than one rotation period. This observability over a full rotation suggests that the observed flare and related CME and dimming originate from a starspot located in a polar region. A very recent study⁴⁹ based on data from the Transiting Exoplanet Survey Satellite suggests that ~60% of all flares on AB Dor occur on its constantly visible polar region, which strongly supports our findings. Light curves for all stellar dimming events are shown in Extended Data Figs. 3-10.

From the stellar light curves, we derived characteristic dimming parameters: (1) the maximum depth, (2) the duration, (3) the rise time from dimming start to maximum depth, (4) the recovery time from dimming maximum back to quiet level, (5) the delay between flare peak and dimming maximum, and (6) the delay between flare peak and dimming start (see 'Determination of stellar dimming parameters and significance' in the Methods). The parameters of all of the stellar dimmings we identified and information on the host stars are listed in Supplementary Table 2. The distributions of these parameters are shown in Fig. 4, along with the same plots for the solar dimmings identified in the SDO-EVE 15-25 nm light curves (see 'SDO-EVE Sun-as-a-star solar dimming identification and CME association' in the Methods). The stellar dimming depths range from 5% to 56%, which is an order of magnitude larger than the solar dimming depths. This difference can be explained as an observational selection effect: the quiescent levels of stellar light curves show much larger variances; therefore, only strong dimmings can be identified. The dimming rise times are similar in both cases, with a mean of roughly 2h. Due to subsequent flares or the end of observations, the duration and recovery times represent a lower limit in most of the stellar dimmings and in at least 17 of the solar dimmings. The time between the flare peak and the dimming start tends to be longer for the stellar dimmings (mean 2.3h) than for the solar dimmings (0.9h). We assume that the larger delay is due to the stronger emission and longer decay times in stellar flares, which therefore obscure the effect of the dimming for a longer period (compare to Fig. 1).

This research has produced systematic detections of coronal dimmings on Sun-like and late-type flaring stars, which are suggestive of flare-related CME occurrence and mass loss. In total, we identified 21 CME candidates on 13 different stars, which is larger than the total number of all previous stellar CME detections reported^{10–25}. The accordance of the characteristics of the stellar dimmings with solar dimmings identified in Sun-as-a-star broadband EUV data and their relation to the spatially resolved EUV imagery, as well as the close association between dimmings and CMEs that we established for the Sun, strongly support the interpretation that the stellar dimmings are caused by CMEs. The flux decreases due to the stellar CMEs in the range of 5–56% of the pre-event coronal emission are an order of magnitude larger than for solar dimmings. Depending on the emission mechanism that dominates the dimming (for example, spectral lines or continuum bremsstrahlung radiation), these findings suggest that the strongest stellar dimmings correspond to the depletion of as much as half of the mass of the star's visible corona by the CME.

Our study provides the foundation for a different approach to detect CMEs on stars, which may be extended towards estimations of their masses and speeds. These parameters are key to a better characterization of the contribution of CMEs to the loss of mass and angular momentum by stars as well as the atmospheric escape and habitability of exoplanets6-8. The information derived will be maximized by the combination of dimming observations with physics-based simulations of stellar eruptions. A recent proof-of-concept study showed that magnetohydrodynamic simulations have the potential to quantitatively study stellar CMEs based on their coronal dimmings⁵⁰. Interestingly, an increase of the magnetic flux in the erupting flux-rope in these simulations to make the step from the solar to the more energetic stellar case suggested that stellar dimmings occur at higher temperatures of about 5 million K. This implies that stellar dimmings should be well visible in the EUV, as well as the in X-ray domain, in line with the stellar dimming observations presented here. Future missions at EUV and X-ray wavelengths with higher sensitivity are expected to provide us with many more coronal dimming observations that will be used for stellar CME detections and characterizations. The dimming approach would be further strengthened by coordinated observations in other wavelength regions, such as optical spectroscopy, to obtain complementary information and to identify associated mass flows.

Methods

SDO-EVE Sun-as-a-star solar dimming identification and CME association. SDO-EVE measures the spatially unresolved solar spectral irradiance (Sun-as-a-star) over the wavelength range 6-105 nm. The main instrument is the Multiple EUV Grating Spectrograph (MEGS), consisting of a grazing-incidence spectrograph (MEGS-A, 6-37 nm) and a two-grating, cross-dispersing spectrograph (MEGS-B, 35-105 nm), both with a spectral resolution of 0.1 nm (ref. 38). EVE Level-2 spectral data were used over the whole wavelength interval, with a 0.02 nm spectral binning and a 10 s cadence. From these Level-2 data, we created broadband light curves by integrating the spectra over the wavelength range 15-25 nm, in which coronal dimmings are well observed. For each event, we generated a light curve that covers a duration of 12 h, starting 60 min before the commencement of the associated GOES X-ray flare. To enhance the signal-to-noise ratio and for better comparison to the stellar observations, the data were rebinned to 5-min intervals. The pre-event quiet level was determined as the mean of the last nine 5-min data points before the flare start, and the corresponding standard deviation was used to give an estimate of the errors on the data points. For robustness, the dimming parameters (Fig. 4a-f, Supplementary Table 1) were determined from the 15-25 nm light curves smoothed with a weighted spline fit.

Our solar dataset is based on two extensive lists of large solar flares that cover the full SDO-EVE era and that have been classified in previous, independent studies into eruptive or confined events; that is, into flares with or without an accompanying CME. The sample of ref. 39 comprises 44 flares of GOES class M5.0 and larger that took place within 50° of the Sun centre (32 eruptive, 12 confined) from January 2011 to December 2015. The sample from ref. 37 study covers 42 X-class flares (33 eruptive, 9 confined) without any constraints on the source location (it also includes flares on the limb) that occurred from February 2011 to November 2014. We note that the lists overlap partially, as 17 events appear in both catalogues. The SDO-EVE MEGS-A spectrograph was operational from 30 April 2010 to 26 May 2014. Twenty-eight events from ref. 39 and 31 events from ref. occurred during the period of EVE operations, with 11 events included in both lists. This results in a total of 48 large flares. Four of the events had to be removed from further analysis due to one of the following reasons: incomplete EVE data coverage, a too close succession of a major flare, or no available clear pre-flare level. The final EVE dataset for our Sun-as-a-star analysis therefore comprises 44 large flares (38 eruptive, 6 confined). To increase the statistics, in particular for confined flares, we expanded the analysis by using also the SDO-AIA 19.3 nm filtergrams, which are centred at an EUV spectral line that is very prominent in dimmings (also see the spectrum in Fig. 1). We used AIA 19.3 nm image sequences with a 5 min cadence, from which we created guasi-Sun-as-a-star light curves by summing for each time step the counts of all pixels of the image. In this way, we analysed all of the events listed in the two catalogues37,39 with the same methods as for the SDO-EVE light curves, which resulted in 68 large flares (52 eruptive, 16 confined).

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To use solar dimmings as a benchmark to evaluate whether dimmings are a viable means for CME detection in solar-like and late-type stars, one needs to quantify several aspects. The first is the fraction of CMEs accompanying large solar flares that reveal a significant dimming in the EVE broadband Sun-as-a-star light curves. If this is a large fraction, then by solar-stellar analogy, the dimming phenomenon has a high potential to appear also in stellar flares associated with CMEs. The second is the probability of false positives; that is, the number of cases for which a significant dimming in the aftermath of a large flare is detected without an associated CME. It is important that this number be small compared to the number of real detections to make sure that the identified dimmings associated with flares are likely due to a CME accompanying the flare and not caused by some other variability in the full-Sun light curves. The third is the conditional probability that a CME occurs given that a coronal dimming is detected in the aftermath of a large flare. If this probability is high, it provides strong evidence that coronal dimmings are a good proxy for CMEs. For the determination of the significance of coronal dimmings detected in the SDO-EVE 15-25 nm light curves (as well as in the AIA 19.3 nm integrated light curves), we used an approach similar to that for the stellar case (see 'Determination of stellar dimming parameters and significance' below). The only difference is that for the solar case we demanded that the interval between the time of the flare peak in the EVE broadband light curve and the time at which the emission dropped below the level that marks a significant dimming be \leq 3 h. This criterion was applied to ensure robust associations between the flare and dimming, and to have clear objective rules by which to determine the entries for the contingency table, whether a flare was followed by a significant dimming and whether this dimming relates to a CME. We note that this allowed time frame is substantially longer than the typical rise time to the dimming maximum in spatially resolved observations ($< 40 \text{ min in } 90\% \text{ of } cases^{30}$), in which the dimming tends to start simultaneously with the flare (Fig. 1).

The calculation of the characteristic dimming parameters, such as the maximum emission drop relative to the pre-event level, dimming rise time, duration and so on was done in the same way as for the stellar light curves (see 'Determination of stellar dimming parameters and significance' below). For the solar case, we implemented an automatic algorithm with the following rules. The dimming start was defined by the time at which the spline fit to the data drops below the pre-flare level. For the dimming maximum, we differentiated two cases. If the EUV flux returned to the pre-event level within the 12-h time span under study, the deepest minimum between the start and end of the dimming period was used to define the maximum dimming drop. In the other cases (17 out of 44, indicated in Fig. 4b,d), the dimming maximum was defined by the first significant global minimum of the spline fit to the data that was reached after the detected dimming start.

Calculation of spatially resolved flare and dimming light curves from SDO– **AIA.** To derive spatially resolved light curves of the flare and the coronal dimming regions shown in Fig. 1, we used EUV images from the SDO–AIA 19.3 nm filter, centred at Fe xII (log T = 6.2) and Fe xXIV (log T = 7.2) emission lines³¹. To derive the dimming light curve, at each time step we segmented the instantaneous dimming region using a logarithmic base-ratio detection algorithm³¹. To quantify the absolute changes, we summed up the corresponding pixel values subtracted by the pre-event counts. To derive the segmented flare light curve, we detected at each instant all pixels that had counts exceeding the pre-event level by 50% and summed up the values of all those pixels subtracted by the pre-event counts. To reduce the effect of CCD blooming on the flare masks, only pixels that were identified as flare pixels over at least 3 min were considered. The error ranges plotted in the spatially resolved flare and dimming light curves in Fig. 1 are calculated by varying the thresholds by ±5%.

Sample selection of solar-like and late-type flaring stars. We have searched data archives of missions operating at EUV and soft X-ray wavelengths for flares observed on Sun-like and late-type (F, G, K and M) main-sequence and pre-main-sequence stars. Using the approach described below, we identified observations from 201 stars suitable for our study (XMM-Newton: 51, Chandra: 114 and EUVE: 36).

XMM-Newton. The XMM-Newton Observatory⁴³ provides observations with three X-ray imaging detectors (European Photon Imaging Cameras (EPIC) PN, MOS1 and MOS2), a high-resolution spectrograph and an optical and UV monitor (OM). The EPIC imaging detectors operate in the energy range 0.2–12 keV (0.1–6 nm, refs. ^{52,53}). We used the XMM-Newton flare catalogue⁴ as the basis for selecting events suitable for our study, and we visually inspected all ~100 light curves that were classified as flares. The selected events were required to fulfil the following criteria: full coverage (including the pre-flare and post-flare phases) of at least one flare event and sufficient duration of the flare observation and/or sufficiently high count rate. This last criterion removed events with only one time bin classified as flaring. We compiled the data of all stars that exhibited flare observations fulfilling these criteria, and removed all stars from the sample that are not of spectral types F, G, K or M. Furthermore, we removed binaries, except those either with well-separated

components or that consist of a Sun-like primary with a close M dwarf, brown dwarf or white dwarf secondary, for which it can be assumed that the X-ray emission is dominated by the primary. We removed all evolved stars but kept most pre-main-sequence stars except for classical T-Tauri stars, which may show signatures of accretion events in their light curves. This approach resulted in 36 events on 30 stars from the XMM-Newton flare catalogue⁴. Since the catalogue only includes observations up to the year 2007, we also evaluated more recent observations of the selected stars, identifying 7 more observations with suitable flares. In addition, we searched for data of a sample of well-known active flare stars⁵⁴ and identified 11 more with 23 suitable observations. Finally, we checked the XMM-Newton Serendipitous Source Catalogue (3XMM-DR8). By selecting variable sources with sufficiently high count rates and detected variability, we found 20 additional events from visual inspection of the automated light curve plots provided. Altogether, this yielded 86 observations of 51 different stars that were selected for further analysis of flare-associated dimmings.

EUVE. The EUVE (ref. ⁴², 1992–2001) carried four telescopes, the Deep Survey telescope (DS, 8–18 nm) and the short- (7–18 nm), medium- (17–37 nm) and long-wavelength (30–75 nm) spectrometers. No EUVE flare catalogue exists, but there are studies on the flare activity of late-type main-sequence stars⁵⁵. We used the category 'late' in the Mikulski Archive for Space Telescope search form, which yielded 79 stars (not excluding binaries), from which we extracted a final target list of 36 late-type main-sequence stars with a combined total of 70 observations.

Chandra. The Chandra X-ray Observatory⁴⁴ carries four science instruments, the High Resolution Camera (HRC; 0.06–10 keV), the Advanced CCD Imaging Spectrometer (ACIS, 0.08–10 keV), the High Energy Transmission Grating Spectrometer (HETGS, 0.4–10.0 keV) and the Low Energy Transmission Grating Spectrometer (LETGS, 0.4–10.0 keV). The latter two operate with ACIS. LETGS operates also with HRC, covering an energy range of 0.07–10.0 keV. No Chandra flare catalogue exists. Therefore, we used the Chandra category search, selecting all instruments and using the category 'Stars and WD'. We restricted the search to exposure times > 5,000 s to cover flares, including pre-flare periods. This search yielded 147 stars, including 114 late-type pre- and main-sequence stars with a combined total of 195 observations. We did not exclude binaries in this target sample.

Data preparation. *XMM-Newton.* For all events under study, we downloaded the odf files from the XMM-Newton Science Archive. Light curves were created using data from the three EPIC imaging detectors, using all three detectors in the initial analysis step. Usually, all operate simultaneously, but in a few cases some detectors ran for longer and may cover a part of the flare that is not included in the other exposures. In the case that all exposure times were similar, in general we preferred to use the PN data because of their higher count rates. The XMM-Newton Scientific Analysis System (SAS) version 17.0.0 was used for the data analysis. The SAS tasks epproc and emproc were used to create event lists from the downloaded odf files for the PN and MOS detectors, respectively. For observations included in 3XMM-DR8, we used the source and background extraction regions from the catalogue. In all other cases, we manually selected circular regions from the EPIC images using ds9 and placed the background on a source-free region, preferably on the same CCD.

For each event, we created light curves using the SAS task evselect, which was also used to create different energy binnings. Background subtraction and necessary corrections (vignetting, bad pixels, detector gaps and so on) were carried out with the task epiclccorr. To check whether the considered observations are affected by pile-up, we used two approaches. First, we created diagnostic plots using the SAS tool epatplot. As this only shows whether the whole observation is affected by pile-up, we also used the limiting fluxes from literature⁵⁶. In most observations, only the flare peaks exceeded the pile-up limits, whereas the pre- and post-flare data were not affected. Therefore, in the subsequent analysis, we did not correct for pile-up, as dimmings are characterized by fluxes even below pre-flare levels. We note that, although pile-up affects the different detectors differently, we found that the light curve morphology is similar in all available exposures with sufficient signal-to-noise ratios. If available, the simultaneous optical monitor data were reduced with the SAS tasks omfchain (fast mode) and omichain (imaging mode), respectively. Usually, we preferred to use the fast mode observations because of their higher time resolution, but we used the imaging mode data if fast mode data were not available.

EUVE. EUVE data were retrieved using the Mikulski Archive for Space Telescope, selecting night-time observations only (as daytime observations are contaminated by geocoronal emission), and reduced with the euv1.9 package in the Image Reduction and Analysis Facility software, version 2.15. We used the X-ray PROS (version 2.5) package in the same software, selecting the sources by circles with radii of 25–50 pixels and the background by annuli with radii of 25–100 pixels. For light-curve extraction (background subtracted), we used the task ltcurv in the X-ray PROS package, in which we set the time binning as well as the task effexp in the EUV package to account for instrument and telemetry dead times and vignetting.

NATURE ASTRONOMY

Chandra. We analysed Level-2 event files provided in the Chandra data archive using the Chandra Interactive Analysis Observations software package. For the non-grating observations, we used the task dmextract to extract background-subtracted light curves. For the grating observations, we used the Interactive Spectral Interpretation System software task agle. For the Chandra grating data, we did not subtract a background because of low background levels. Data pile-up can have severe effects on the data analysis for Chandra ACIS data. For Chandra HETGS observations in higher orders (excluding 0th order), pile-up has only a small effect, as in the higher orders no high count rates are evident in single pixels. As all our events were detected in light curves constructed from higher-order HETGS data, we did not apply pile-up correction.

Light-curve binning. For each event, we created light curves in the full available energy range, as well as several subbands. We inspected X-ray spectra of active Sun-like stars57, and for XMM-Newton and Chandra, we selected energy ranges in which strong spectral lines are formed at similar temperatures (0.6- $1.2 \text{ nm} \approx 1-2 \text{ keV:} \log [T(K)] \approx 7.0; 1.2-1.7 \text{ nm} \approx 0.73-1 \text{ keV:} \log [T(K)] \approx 6.7; \text{ and}$ $1.7-6 \text{ nm} \approx 0.2-0.73 \text{ keV}$: log [T(K)] ≈ 6.3). This approach allowed us to study whether the identified dimmings occur at specific temperatures. Then, all light curves were inspected to select possible dimming candidates, which were defined to have characteristics that resemble those of the solar observations. The flux was required to drop below the pre-flare level by at least 2σ (see 'Determination of stellar dimming parameters and significance' below) in one or more energy bands after the flare and to return back towards the pre-flare level after reaching a minimum. Events for which no sufficiently long (>0.5 h) pre-flare level was available were removed from further analysis. In total, 21 stellar dimming candidates were identified that fulfil these criteria. In some cases, the observation ended before the flux returned to the pre-flare level. We derived the same set of dimming parameters as for the Sun (Supplementary Table 2). As stellar light curves usually are more noisy than solar observations, we determine the dimming parameters from weighted cubic-spline fits to the flux curves.

The time binning was chosen individually based on the quality of the light curves. The obtained parameters depend slightly on the chosen time binning, but the spline fit was usually quite similar for time binnings that were not too coarse. To assess the significance of the detected dimmings, we needed to obtain the uncertainty of the 'quiet' flux level. This, however, depends strongly on the chosen time binning, as the typical errors on the count rate decrease with increasing bin size. Therefore, the significance also increases with bin size. To obtain a more objective way to evaluate the uncertainties, we optimized the time binning for selected events by analysis of the Rayleigh periodogram of the raw event lists, for which only the extraction of the source region and selection of the energy interval has been applied. By fitting the resulting Rayleigh periodograms with a power-law-plus-constant model, an optimal bin size for light curves can be obtained that best separates statistical noise from intrinsic variability58. We constructed this periodogram for all selected light curves between frequencies that correspond to the duration of the observation and the mean count rate. For fitting, we minimized the B statistic using the Nelder-Mead algorithm. The optimal bin size was calculated as a function of the fit parameters58. We found that the light curves obtained with optimized binning and the spline fits to the data using smaller time binning are very similar in most cases, and the derived maximum dimming depths from both methods are consistent.

Determination of stellar dimming parameters and significance. The determination of the dimming parameters depends on the choice of the quiet pre-flare level (flux $_{quiet}$), determined as the mean flux in the quiet time interval. This quiet interval was chosen to be immediately before the considered flare events, preferably covering a period > 1 h with low variability. Relative to this level, we defined the start time of the dimming t_{ds} , at which the weighted spline fit applied to the data drops below the quiet level for the first time after the flare. The minimum time t_{dm} , defined by the time of the first minimum of the spline fit (flux_{dm}) after the dimming start, was used to evaluate the maximum dimming depth as $(flux_{quiet} - flux_{dm})/flux_{quiet}$. The dimming end t_{de} is defined as the first point after the dimming maximum at which the spline fit returns to the quiet level. Small flares that interrupt the dimming, but for which the flux clearly drops below the quiet level again afterwards, are masked out from the dimming parameter determination. However, in all but three cases, either strong flares ended the dimming or the end of the observation was reached. Therefore, the calculated recovery times and durations of the stellar dimmings give lower limits.

To assess the significance of the dimming, we needed to estimate the errors of the maximum dimming depths, which include the mean error of the quiet flux and the mean error of the flux in the dimming region. The mean error of the quiet flux includes the contributions of both the error of the mean flux determined from the errors of the individual data points $(\sigma_{p}, i = 1, ..., N_{quiel})$ and the variance of the data points in the quiet interval, $\sigma_{quiel}^2 = \sum_i (\sigma_i/N_{quiel})^2 + \text{var}(flux_{quiel})$. This provides a maximum estimate of the mean error of the quiet level. The mean error of the dimming maximum (flux_{dm}) includes both the contributions from the spline fit (rms error) and the mean error of the flux in the dimming region (t_{ds} to t_{do}), $\sigma_{dm}^2 = \sum_j (flux_{dm} - fit)^2/N_{dm} + \sum_j (\sigma_j/N_{dm})^2 (j = 1, ..., N_{dm})$, again providing a maximum gregion to be more representative than the error of a single data point at

the maximum dimming depth. The error of the maximum dimming depth in flux units, depth = flux_{quiet} – flux_{im}, was found by error propagation, $\sigma_{depth}^2 = \sigma_{quiet}^2 + \sigma_{dm}^2$. The error of the maximum dimming depth in percent is $\sigma_{ss}^2/\text{depth}_{ss}^2 = \sigma_{depth}^2/$ depth² + σ_{auiet}^2 /flux_{auiet}². We considered dimmings to be significant if in at least one of the energy-binned light curves, the maximum dimming depth was larger than twice its error (> $2\sigma_{\%}$). Some dimming events may therefore be significant only in one energy band, and some are significant only if the optimal binning method is used. For the final results, we adopted the parameters derived from the spline fit method, because the timing parameters of the dimmings (duration, start, minimum, end time and so on) would have large uncertainties because of the much coarser time binning obtained with the optimized binning method. Also, with this method, the binning differed between different energy bands for the same event, which made comparisons more difficult. The time of the flare maximum was taken from the original data, as the spline fit was not a good approximation of the sharp flare peaks. The stellar dimming parameters summarized in Supplementary Table 2 and Fig. 4 were derived from the total energy band. Therefore, the dimming depth listed in column 7 of Supplementary Table 2 is not > $2\sigma_{\%}$ for all cases, as some dimmings were significant only in smaller subbands. The significance of the dimmings is indicated by different colours of the shadings in Extended Data Figs. 3-9. We note that due to the long duration of the dimmings (typically > 1 h), the significance of the total flux deficit (that is, over the whole dimming region), is much larger than that of the maximum dimming depth alone.

Spectral fitting. For the two dimmings of Proxima Centauri (Fig. 2), we evaluated how the plasma temperature and emission measure vary during the observation. We used the X-ray spectral fitting package XSPEC to fit spectra in selected time segments that cover the whole light curves (each spectrum was required to have > 3,000 counts). The source+background and background spectra were created using the SAS task evselect, and rmfgen and arfgen were used to generate redistribution matrix and auxiliary response files. We grouped the files with specgroup, which we used also to bin the spectra with a minimum of 20 counts per bin, while not oversampling the intrinsic resolution by a factor of 3. The model we chose includes an absorbing column (which represents absorption by the interstellar medium and is set to $\log N_{\rm H} = 17.61$, where in $N_{\rm H}$ is the column density of hydrogen atoms)59, and several Astrophysical Plasma Emission Code models that represent the components of coronal plasma at different temperatures. The 'quiet' pre-flare level was fitted first with one or more plasma components, and we checked whether adding further plasma components would significantly improve the fit. Then, we used this 'quiet' solution as a fixed input for the flare bins, but we added further plasma components to represent the flare. For the dimming regions, we used only the quiet solution as a starting value, and did not fix any parameters. We performed a simultaneous fit to all three detectors, but allowed for a constant offset between detectors to account for uncertainties in the absolute calibration60. We found that the quiet and dimming intervals are best fit with two plasma components, whereas the flaring intervals are best represented by three. Then, we calculated the total emission measure (EM = $\sum_{i} EM_{i}$, for *i* plasma components) and the EM-weighted temperature $(T = \sum_i (T_i EM_i)/EM)$.

Data availability

The solar data used in this study are publicly available from the SDO–EVE data archive (http://lasp.colorado.edu/eve/data_access/eve_data/products/level2/) and the SDO–AIA data archive (http://jsoc.stanford.edu/ajax/lookdata.html?ds=aia. lev1_euv_12s). The stellar data used in this study are publicly available at the XMM-Newton Science Archive (http://nxsa.esac.esa.int/nxsa-web/#search), the Chandra Data Archive (http://nksa.esac.esa.int/nxsa-web/#search), the Chandra Data Archive (http://cda.harvard.edu/chaser/) and the EUVE data archive at the Mikulski Archive for Space Telescopes (https://archive.stsci.edu/euve/search.php). The specific stellar datasets used in this study are uniquely identified by their archive's Observation ID given in Supplementary Table 2. The resulting solar and stellar dimming parameters are given in Supplementary Tables 1 and 2.

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Author contributions

A.M.V. conceptualized and led the study, co-designed its solar part and led the writing. P.O. co-designed the stellar part of the study and analysed the XMM-Newton data. M.L. co-designed the stellar part of the study and analysed the Chandra and EUVE data. K.D. co-designed the solar part of the study and analysed the SDO–AIA data. N.C.F. analysed the SDO–EVE data. H.S.H. contributed to the SDO–EVE spectral analysis. All authors discussed the results and contributed to the manuscript text.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 Selected examples illustrating the manifold of coronal dimming appearances for CME-associated solar flares. Top subpanels: GOES full-Sun 0.1–0.8 nm soft X-ray flux, dominated by the hot flare emission. Bottom subpanels: SDO/EVE full-Sun 15–25 nm light curves showing the flares and coronal dimmings. The red line shows the weighted cubic spline fit. Green data points are used for calculation of pre-flare level. Horizontal lines represent the pre-flare (solid) and corresponding 2σ (dashed) level used to identify significant dimming emission decreases. Vertical lines indicate the times of the dimming start, maximum depth and end.



Extended Data Fig. 2 | Selected examples of light curves for confined solar flares. a) A confined flare (GOES class M4.9) which shows no dimming (true negative), b) the only confined flare (GOES class M6.3) where a significant EVE dimming was identified (false positive). Note that starting around 05:00 UT on 2 Nov 2013 there is a pronounced dimming associated with an eruptive C8.2 flare. Same plot format as Extended Data Fig. 1.



Extended Data Fig. 3 | Background subtracted X-ray light curves of the fast-rotating K-type star AB Dor. Data from the XMM EPIC PN (left and right columns) and MOS1 (middle column) detectors are shown as filled symbols, and are plotted for the total energy band (0.2–12 keV) as well as four subbands. Bin sizes of 100s, 200s, and 100s were used (from left to right). The weighted spline fits to the data are shown as blue lines, the adopted quiet levels as red dashed lines. The quiet time intervals are indicated as gray shaded areas, the detected dimming regions as blue shaded areas (dark blue: maximum dimming depth $>2\sigma_{sy}$. Jight blue: maximum dimming depth $<2\sigma_{sy}$). The time is given in hours relative to the start of the PN or MOS1 exposures. The right y-axes give the relative differences in per cent between the quiet levels and the data. The upper x-axes show the stellar rotation phase, starting from the beginning of the observations. Error bars are the errors returned by the *epiclccorr* task. Small dark gray symbols visible in some panels indicate the background light curve in the same energy band. No simultaneous photometric observations are available for the event shown in the left column. For the other two events, simultaneous photometric fast mode observations in the UVW2 (middle) and UVM2 (right) bands are shown in the lowest panels. The fast mode data were rebinned to 200s. Bin widths are indicated by the horizontal bars, count rate errors were determined by standard error propagation of the errors returned by the *omfchain* task for the standard 10s binning. The dimming event in the middle column is only significant with the optimized binning method.

NATURE ASTRONOMY



Extended Data Fig. 4 | Background subtracted X-ray light curves of the fast-rotating K-type stars AB Dor (left column), CD-53 544 (middle column) and LO Peg (right column). Data from the XMM EPIC PN detector are shown as filled symbols, and are plotted for the total energy band (0.2-12 keV) as well as four subbands. Bin sizes of 100s, 300s, and 100s were used (from left to right). The weighted spline fits to the data are shown as blue lines, the adopted quiet levels as red dashed lines. The quiet time intervals are indicated as gray shaded areas, the detected dimming regions as blue shaded areas (dark blue: maximum dimming depth $>2\sigma_{9c}$, light blue: maximum dimming depth $<2\sigma_{9c}$). The time is given in hours relative to the start of the PN exposures. The right y-axes give the relative differences in per cent between the quiet levels and the data. The upper x-axes show the stellar rotation phases, starting from the beginning of the observations. Error bars are the errors returned by the *epiclccorr* task. Small dark gray symbols visible in some panels indicate the background light curve in the same energy band. Simultaneous photometric imaging mode observations in the UVW2 bands (left), as well as fast mode observations in the UVW1 (middle; data in other bands before and after the event are omitted due to their different flux level) and UVM2 (right) bands are shown in the lowest panels. The fast mode data were rebinned to 400s. In the left column, exposure times are indicated by the horizontal bars, magnitude errors are the errors returned by the *omichain* task. In the other columns, bin widths are indicated by the horizontal bars, count rate errors were determined by standard error propagation of the errors returned by the *omichain* task for the standard 10s binning.



Extended Data Fig. 5 | Background subtracted X-ray light curves of the G-type stars 47 Cas B (left column), EK Dra (middle column) and VB 50 (**right column).** Data from the XMM EPIC PN detector are shown as filled symbols, and are plotted for the total energy band (0.2–12 keV) as well as four subbands. Bin sizes of 400s, 300s, and 400s were used (from left to right). The weighted spline fits to the data are shown as blue lines, the adopted quiet levels as red dashed lines. The quiet time intervals are indicated as gray shaded areas, the detected dimming regions as blue shaded areas (dark blue: maximum dimming depth $>2\sigma_{sc}$, light blue: maximum dimming depth $<2\sigma_{sb}$). The time is given in hours relative to the start of the PN exposures. The right y-axes give the relative differences in percent between the quiet levels and the data. Error bars are the errors returned by the *epiclccorr* task. Small dark gray symbols visible in some panels indicate the background light curve in the same energy band. No simultaneous photometric observations are available for 47 Cas B and VB 50. For EK Dra, simultaneous photometric imaging mode observations in the UVW2 band are shown in the lowest panel. Exposure times are indicated by the horizontal bars, magnitude errors are the errors returned by the *omichain* task. The dimming event of EK Dra is only significant (maximum dimming depth $>2\sigma_{sc}$) with the optimized binning method.

NATURE ASTRONOMY



Extended Data Fig. 6 | Background subtracted X-ray light curves of the young M-type star AU Mic. Data from the XMM EPIC PN detector are shown as filled symbols, and are plotted for the total energy band (0.2-12 keV) as well as four subbands. Bin sizes of 300s were used. The weighted spline fits to the data are shown as blue lines, the adopted quiet levels as red dashed lines. The quiet time intervals are indicated as gray shaded areas, the detected dimming regions as blue shaded areas (dark blue: maximum dimming depth $>2\sigma_{sc}$, light blue: maximum dimming depth $<2\sigma_{sg}$). The time is given in hours relative to the start of the PN exposures. The right y-axes give the relative differences in per cent between the quiet levels and the data. Error bars are the errors returned by the *epiclccorr* task. Small dark gray symbols visible in some panels indicate the background light curve in the same energy band. Simultaneous photometric fast mode observations for the event shown in the right column are omitted, as they are corrupted after the first 7 hours of the observation. For the other two events, simultaneous photometric fast mode observations in the UVW2 band are shown in the lowest panels. The fast mode data were rebinned to 300s. Bin widths are indicated by the horizontal bars, count rate errors were determined by standard error propagation of the errors returned by the *omfchain* task for the standard 10s binning.



Extended Data Fig. 7 | Background subtracted X-ray light curves of the M-type stars CN Leo (left column), GJ 669 AB (middle column) and GSC 07396-00759 (right column). Data from the XMM EPIC PN detector are shown as filled symbols, and are plotted for the total energy band (0.2-12 keV) as well as four subbands. Bin sizes of 100s, 200s, and 1000s were used (from left to right). The weighted spline fits to the data are shown as blue lines, the adopted quiet levels as red dashed lines. The quiet time intervals are indicated as gray shaded areas, the detected dimming regions as blue shaded areas (dark blue: maximum dimming depth $>2\sigma_{96}$, light blue: maximum dimming depth $<2\sigma_{96}$). The time is given in hours relative to the start of the PN exposures. The right y-axes give the relative differences in per cent between the quiet levels and the data. Error bars are the errors returned by the *epiclccorr* task. Small dark gray symbols visible in some panels indicate the background light curve in the same energy band. For GJ 669 AB, the available imaging photometry consists of one image in each filter band, which cannot be used to create a photometric light curve. For CN Leo, they were omitted, as the fast mode observations are corrupted and the imaging mode observations have a too low cadence. For GSC 07396-00759, the imaging mode observations are also omitted because of their too low cadence. Moreover, the last few hours of this observation (time>30h) are affected by a strong background flare, making the data in the highest energy bin (lowest panel) unusable. The dimming events of CN Leo and GJ 669 AB are only significant with the optimized binning method.



Extended Data Fig. 8 | Background subtracted X-ray light curves of Proxima Cen. Data from the XMM EPIC PN (left) and MOS1 (right) detectors are shown as filled symbols, and are plotted for the energy band 0.2-2 keV as well as four subbands (in both cases, data from 2-12 keV are not usable). Bin sizes of 200s and 400s were used (from left to right). The weighted spline fits to the data are shown as blue lines, the adopted quiet levels as red dashed lines. The quiet time intervals are indicated as gray shaded areas, the detected dimming regions as blue shaded areas (dark blue: maximum dimming depth $>2\sigma_{s_0}$, light blue: maximum dimming depth $<2\sigma_{s_0}$). The time is given in hours relative to the start of the PN or MOS1 exposures. The right y-axes give the relative differences in per cent between the quiet levels and the data. Error bars are the errors returned by the *epiclccorr* task. Small dark gray symbols visible in some panels indicate the background light curve in the same energy band. Simultaneous photometric fast mode observations in the U band are shown in the lowest panels. The fast mode data were rebinned to 100s (left) and 300s (right). Bin widths are indicated by the horizontal bars, count rate errors were determined by standard error propagation of the errors returned by the *omfchain* task for the standard 10s binning.



Extended Data Fig. 9 | Chandra ACIS HETGS light curves of the rapidly rotating young star PZ Tel (left panels) and the young binary star EQ Peg (right panels). The data are plotted for the total energy band (0.4–12 keV) as well as three subbands. All light curves are binned to 500s. The weighted spline fits to the data are shown as blue lines, the adopted quiet levels as red dashed lines. The quiet time intervals are indicated as gray shaded areas, the detected dimming regions as blue shaded areas (dark blue: maximum dimming depth > $2\sigma_{\psi}$, light blue: maximum dimming depth < $2\sigma_{\psi}$). The right y-axes give the relative differences in per cent between the quiet levels and the data. The upper x-axes show the stellar rotation phases, starting from the beginning of the observations. Error bars are the errors returned by the *aglc* task. The first dimming event of PZ Tel is only significant with the optimized binning method.



Extended Data Fig. 10 | Background subtracted X-ray (0.2-12 keV) light curves of Proxima Cen. This plot includes all eight available XMM observations with EPIC data, spanning the years from 2001 to 2018. Here we use the MOS1 exposures, because of their slightly longer durations than the PN exposures of the same observations. The dimming events are included in the last two observations. Error bars are omitted here for clarity. This representation shows that the dimming events are associated with small short flares, which can be understood in terms of better observability of the dimming compared to the bright flare emission.