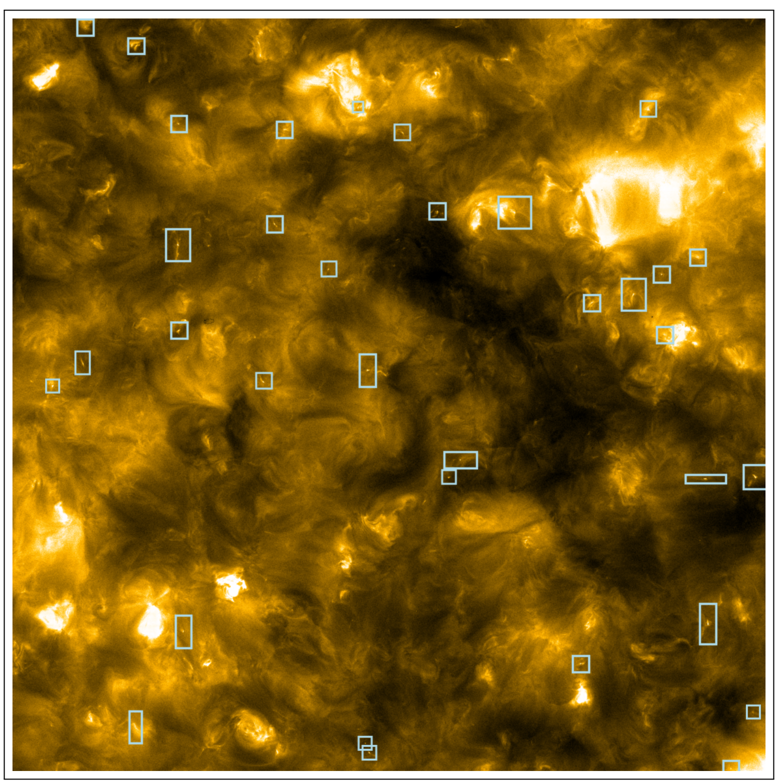
Detecting Campfires in Solar Orbiter's Extreme UV Imager Data

Project Summary

Sven Seso, 30. November 2025

Abstract

Campfires are small-scale brightening events in the solar corona, which were discovered in 2020 in high-resolution EUV images from Solar Orbiter's Extreme Ultraviolet Imager (EUI). Current understanding of their statistical properties is incomplete, even though they are believed to play an important role in the coronal heating problem, contributing to EUI's role in explaining coronal heating, a key ESA science goal. This project developed a fully automated detection pipeline combining multi-stage filtering and simple DBSCAN-based machine learning approaches to identify and characterize campfires in EUI/HRI$_{\mathrm{EUV}}$ (174 Å) data, visualization tools for high-quality image and video exports, as well as simple computations of physical properties. The results are visually sensible and in essence align with established papers, for example on power-law like lifetime and area distributions and a realistic detection rate between 400-1300 detections for the 2020-05-30 dataset, aligning with literature (Berghmans et al. 2021), as well as a positive correlation between intensity and area ($\rho = 0.699$, $p = 5.59 \cdot 10^{-63}$), consistent with expected trends (Narang et al. 2025). However, the current implementation leaves room for improvement in the accuracy of lifetime and area detection, which could be improved with more sophisticated machine-learning techniques, as well as event statistics and their rigorous interpretation.



1 Context

Data from Solar Orbiter's perihelion campaigns offers the highest spatial resolution of the sun's surface to date. As a result, previously unknown, small transient brightenings in the corona (typical areas range from 0.5 Mm^2 to 10 Mm^2), called "campfires", were discovered in Solar Orbiter's first datasets from 2020. To this day, many statistical properties of these events remain unclear, however, campfires are believed to play a significant role in the coronal heating problem, which is why studying them is of highest interest.

2 Goal

The primary goal of this project was to gain experience with tools used in solar physics and image analysis by creating a simple detection pipeline for campfires in Solar Orbiter Extreme UV Imager Data ($\mathrm{HRI}_{\mathrm{EUV}}$-174 Å), high quality image and video exports showcasing the detections, as well as simple approaches for computing physical properties (lifetime, area, intensity, etc.).

3 Methodology

The detection pipeline uses a multi-stage process, combining $n\sigma$-thresholding, connected-component labeling, morphological filtering, and DBSCAN-based spatiotemporal clustering (as precursor to more sophisticated Machine Learning-based feature detection, work in progress). Visualizations were implemented with FFMPEG encoding for video exports, as well as matplotlib/seaborn for plots and image exports.

4 Results

In the 50 frame, 5 second cadence, Level-2 EUI data sequence from 2020-05-30, the pipeline detected 448 events with conservative parameters and 1294 events with looser parameters, which falls in line with observed rates (Berghmans et al. 2021). Below is shown an example frame from that sequence, overlayed with slightly dilated bounding boxes of the detections on the right.

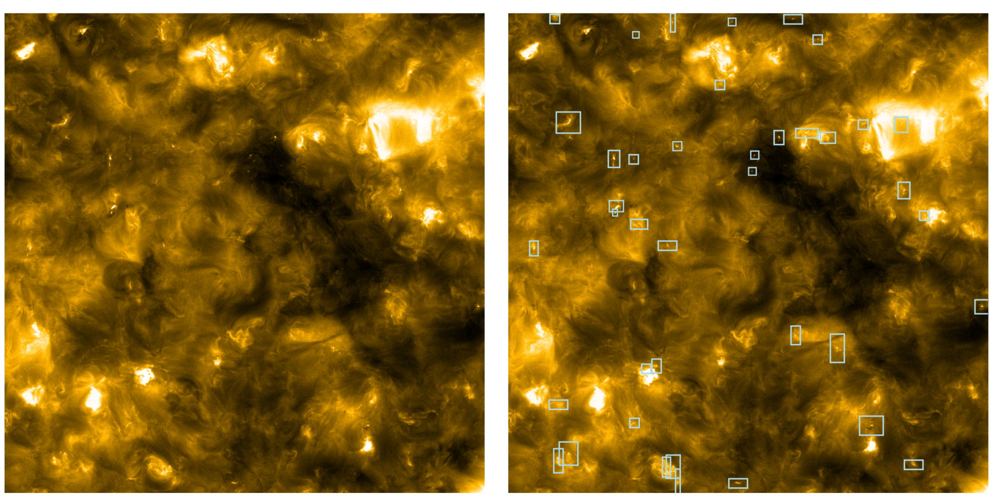


Figure 1: Solar orbiter EUI/$\mathrm{HRI}_{\mathrm{EUV}}$ (174 Å) dataset from 2020-05-30T14:54:53.262, with the original frame on the left, and the detected events on the right.

Let's also look at two sample plots from the obtained event data.

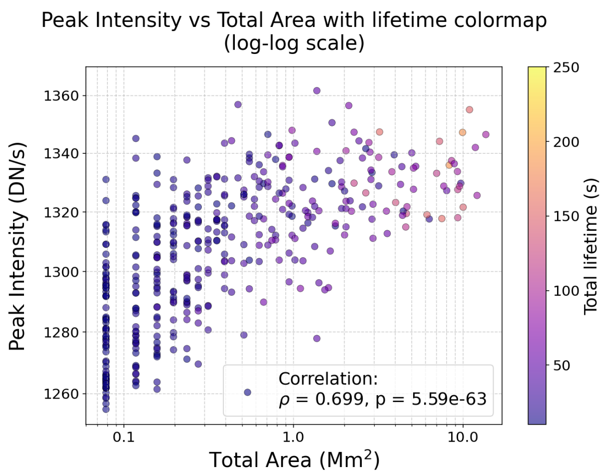


Figure 2: Scatterplot of the peak intensity in [DN/s] against total event area in [Mm^2] shows a positive correlation (Spearman's correlation coefficient of $\rho = 0.699$, $p = 5.59 \cdot 10^{-63}$), with brighter and bigger events tending to live longer, as hinted at by the colormap.

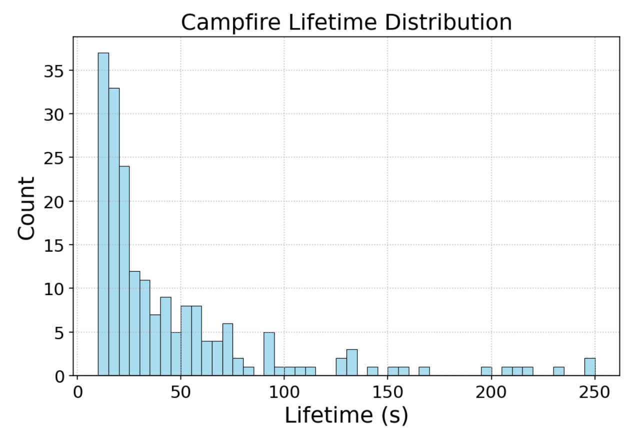


Figure 3: Campfire Lifetime distribution histogram. Most events are short lived, with a steep drop off and a long tail, resembling a power-law or lognormal-fit.

5 Discussion

A critical evaluation of the pipeline confirms its core strengths: It reliably detects visually sensible events and filters out noise effectively (see fig. 1) at rates (448–1294 per 50-frame sequence) that align well with published benchmarks (Berghmans et al. 2021). Plotting Intensity vs. area shows a positive correlation (see fig. 2, Spearman's correlation coefficient of $\rho = 0.699$, $p = 5.59 \cdot 10^{-63}$), with bigger and brighter events tending to live longer (as implied by the colormap), which suggests a positive relationship between area/intensity and lifetime as well, consistent with expected trends (Narang et al. 2025).

Limitations:

The detections also capture a power-law-like or log-normal trend in lifetime distribution (see fig. 3), as observed in literature (Berghmans et al. 2021). However, the histogram is a bit front-heavy with a thinned out tail, which hints at fragmentation in lifetime detections, causing more shorter events. This is confirmed through visual inspection of the exported videos with bounding box overlays, where occasional gap frames become evident, explaining the bias towards shorter/truncated lifetime detections.
Another crude assumption stems from the fact that equal-width binning in the lifetime histogram slightly distorts the short-tail dominance, though the overall shape (steep drop-off with long tail) holds true. A similar power-law like distribution is cited in many papers for other properties such as area, however, plotting a histogram for the areas of detected events currently shows a very long tail, which signals that some detected areas are overestimated. This could be caused by the small-angle pixel-scale approximation used, which disregards solar curvature, leading to increasing errors for detections at the edge of a frame and overestimation of their area.
The biggest opportunity for improvement lies in spatial tracking, as the current implementation cannot recognize moving events (ex. mass ejections), which means the pipeline works well for quiet-sun datasets with little moving components, but detects too many false positives on very active regions.

Suggested Upgrades:

These insights point to targeted upgrades, including:

- correct for solar curvature using heliocentric angle (angle between the local surface normal and the line of sight spacecraft);
- Computer vision based shape classifiers to refine area calculations and reject artifacts;
- ML-driven lifetime tracking for gap free detections;
- add centroid tracking to detect moving events;
- Rigorous statistics tools like Maximum likelihood estimation for power-law fits and Kolmogorov-Smirnov tests for literature comparisons;
- Scaling to larger, finer-cadence datasets available in the public SOAR-archive for truncation-free analysis and higher time resolution.

This project taught me python tools used in solar physics, such as sunpy, astropy and the unsupervised machine-learning tool DBSCAN, FITS data handling and data/image analysis, gave me insight into ongoing research on solar campfires, and made me realize the challenges associated with analyzing and interpreting real physical data, such as handling noise and correct drawing of statistical conclusions from real datasets. With my current results and literature comparison, I compiled several actionable suggestions for improvement, which I will work on implementing in the future.

6 References

- Narang, N., Verbeeck, C., Mierla, M., Berghmans, D., Auchère, F., Shestov, S., Delouille, V., Chitta, L. P., Priest, E., Lim, D., Dolla, L. R., & Kraaikamp, E. (2025). Extreme-ultraviolet transient brightenings in the quiet-Sun corona: Closest-perihelion observations with Solar Orbiter/EUI. Astronomy & Astrophysics, 699, A138. https://doi.org/10.1051/0004-6361/202554650
- Berghmans, D., Auchère, F., Long, D. M., Soubríe, E., Mierla, M., Zhukov, A. N., Schühle, U., Antolin, P., Harra, L., Parenti, S., Podladchikova, O., Aznar Cuadrado, R., Buchlin, E., Dolla, L., Verbeeck, C., Gissot, S., Teriaca, L., Haberreiter, M., Katsiyannis, A. C., Rodriguez, L., Kraaikamp, E., Smith, P. J., Stegen, K., Rochus, P., Halain, J. P., Jacques, L., Thompson, W. T., & Inhester, B. (2021). Extreme UV quiet Sun brightenings observed by Solar Orbiter/EUI. Astronomy & Astrophysics, 656, L4. https://doi.org/10.1051/0004-6361/202140380