Power-law energy distributions of small-scale impulsive events on the active Sun: Results from IRIS

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ABSTRACT
Numerous studies have analysed inferred power-law distributions between frequency and energy of impulsive events in the outer solar atmosphere in an attempt to understand the predominant energy supply mechanism in the corona. Here, we apply a burst detection algorithm to high-resolution imaging data obtained by the Interface Region Imaging Spectrograph to further investigate the derived power-law index, $\gamma$, of bright impulsive events in the transition region. Applying the algorithm with a constant minimum event lifetime (of either 60 s or 110 s) indicated that the target under investigation, such as Plage and Sunspot, has an influence on the observed power-law index. For regions dominated by sunspots, we always find $\gamma < 2$; however, for datasets where the target is a plage region, we often find that $\gamma > 2$ in the energy range [$\sim 10^{23}$, $\sim 10^{26}$] erg. Applying the algorithm with a minimum event lifetime of three timesteps indicated that cadence was another important factor, with the highest cadence datasets returning $\gamma > 2$ values. The estimated total radiative power obtained for the observed energy distributions is typically 10 – 25% of what would be required to sustain the corona indicating that impulsive events in this energy range are not sufficient to solve coronal heating. If we were to extend the power-law distribution down to an energy of $10^{21}$ erg, and assume parity between radiative energy release and the deposition of thermal energy, then such bursts could provide 25 – 50% of the required energy to account for the coronal heating problem.

Key words: methods: statistical – methods: observational – techniques: spectroscopic – Sun: activity – Sun: atmosphere – Sun: corona

1 INTRODUCTION
How the coronae of the Sun and solar-like stars are heated to multi-million degree temperatures remains an open question in modern astrophysics. Typically, energy supply is explained as coming either from magnetohydrodynamic (MHD) waves (Alfvén 1947) or magnetic reconnection (Parker 1988). However, because the spatial scales of dissipation from either mechanism would be so small (km length-scales or less) neither has currently been shown to be dominant in the Sun and other solar-type stars. It is well known that large-scale solar flares are magnetic reconnection events which can release huge amounts of energy ($\sim 10^{22}$ erg) over time-scales of the order of minutes, yet these events are sufficiently rare that their time-averaged energy contribution is not high enough to compensate for the radiative losses of the corona. On sub-arcsecond scales, a host of magnetic reconnection associated features include, but are not limited to, Ellerman bombs (EBs; Ellerman 1917; Vissers et al. 2013; Nelson et al. 2015; Reid et al. 2016), Quiet-Sun Ellerman-like Brightenings (QSEBs; Rouppe van der Voort et al. 2016; Nelson et al. 2017), Explosive Events (EEs; Brueckner & Bartoe 1983; Huang et al. 2017, 2018), and UV bursts (Peter et al. 2014; Nelson et al. 2016; Young et al. 2018) have been shown to be common in the solar atmosphere, but the ability of these features to deposit enough energy to heat the upper layers of the Sun remains uncertain.

Two numbers are often cited by researchers when discussing the ability of magnetic reconnection events to provide the $10^{21}$ erg required to heat the upper layers of the active solar atmosphere (Withbroe & Noyes 1977). The first is that in order to understand whether magnetic reconnection is relevant to coronal heating we must be able to probe nano-flare events with energies less than $10^{22}$ erg (Parker 1988). This work built on Levine (1974) who proposed that coronal heating was due to a multitude of small reconnections. Despite the apparent simplicity of this task, it has so far proved difficult to identify large samples of events at these energies due to the observational stipulations required. Obtaining both the high spatial and temporal resolution needed in the upper layers of the solar atmosphere with a large enough field-of-view (FOV) to provide some general information is still a non-trivial task. The second number often quoted is that in order to explain the heating of the corona by magnetic reconnection events the energy ver-
sus frequency distribution must have a power-law with an index, $\gamma$, steeper than 2 (Hudson 1991). If $\gamma > 2$, magnetic reconnection events with lower energies are important in heating the corona; however, if $\gamma < 2$, higher energy flares are dominant and lower energy events such as nano-flares cannot contribute much to the total power (Krucker & Benz 1998; Parnell & Jupp 2000). Therefore, investigating the frequencies of suitably small impulsive burst events (often assumed to be an observational signature of magnetic reconnection) in the upper atmosphere remains an essential task in solar physics.

Numerous authors have attempted to analyse the power-law distributions of brightenings in the upper solar atmosphere using a variety of data. Shimizu (1995), for example, looked at active region (AR) transient brightenings and found that their frequency distribution as a function of energy had a power-law with an index of 1.64 to 1.89. Interestingly, it was found that the returned power-law index was dependent upon the pixel size with smaller pixels providing larger indices. Notably though, the events studied by Shimizu (1995) had energies in excess of $10^{27}$ erg, well above the $10^{24}$ erg level suggested by Parker (1988). Parnell & Jupp (2000) investigated Transition Region and Coronal Explorer (TRACE; Golub et al. 1999) events with energies in the range $10^{23}-10^{26}$ erg deriving a power-law index greater than two. However, those authors suggested that the input from this energy range was insufficient to heat the quiet solar corona, implying that even smaller energies, down to $10^{21}$ erg, would be required. Aschwanden & Parnell (2002) expanded on this work and looked at TRACE data from the 171 Å and 195 Å filters deriving power-law indices of 1.86 and 1.81, respectively. The above dependence on instrument and pixel scale highlights the importance of temporal and spatial resolution in investigating the smallest and faintest events.

In almost all observational studies conducted to date, the derived power-law index between frequency and energy has not been sufficient to provide enough energy to the upper atmosphere to compensate for radiative losses. There is, therefore, currently very little confirmatory evidence to support the hypothesis that micro/nano-flaring is sufficient to heat the coronae. Analytical and numerical modelling by a host of authors, (e.g., Cargill & Klimchuk 2004; Rappazzo et al. 2008; Parnell et al. 2010; Bowness et al. 2013; Jess et al. 2019; Mondal et al. 2020), offer some hints that further observational studies would be beneficial. Additionally, research on solar-like stars could offer some clues about the contribution of magnetic reconnection to the heating of the upper atmosphere. For example, Doyle & Butler (1985) presented a linear correlation between the X-ray flux of quiescent dMe stars (plus the Sun) against the time-averaged energy emit-
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Table 1. Details of the IRIS SJI observations studied here. The ‘Cadence (s)’ column refers to the IRIS SJI 1400 Å channel cadence. The * indicates that IRIS SJI data are also available with the same cadence.

| Data | Date of Observation | Start Time (UT) | End time (UT) | FOV (arcsec) | (x_c, y_c) (arcsec) | Cadence (s) | NOAA Number | Target | OBSID |
|------|---------------------|----------------|--------------|-------------|---------------------|-------------|-------------|--------|-------|
| Set 1* | 2013/08/31 | 15:59 | 17:54 | 60'' × 61'' | (-332'', 74'') | 12 | 11836 | Sunspot | 4000255147 |
| Set 2* | 2013/12/17 | 00:34 | 01:33 | 167'' × 174'' | (266'', 177'') | 20 | 11921 | Sunspot/Plage | 3820256107 |
| Set 3* | 2014/01/16 | 18:54 | 03:20+1day | 59'' × 60'' | (-122'', 270'') | 19 | 12321 | Sunspot/Plage | 382009270 |
| Set 4* | 2015/11/12 | 02:57 | 03:57 | 120'' × 119'' | (-134'', -298'') | 13 | 12449 | Plage | 3600104017 |
| Set 5* | 2015/11/12 | 15:57 | 16:50 | 120'' × 119'' | (63'', -244'') | 21 | 12449 | Plage | 3600106007 |
| Set 6 | 2017/03/26 | 11:31 | 11:51 | 119'' × 119'' | (-191'', 252'') | 5 | 12643 | Plage | 3613107603 |
| Set 7 | 2017/03/26 | 11:02 | 11:22 | 119'' × 119'' | (-191'', 252'') | 3 | 12643 | Plage | 3613105603 |
| Set 8 | 2017/05/01 | 13:39 | 16:59 | 120'' × 119'' | (-317'', 251'') | 12 | 12654 | Plage | 3620104423 |
| Set 9 | 2016/06/06 | 13:59 | 16:51 | 120'' × 119'' | (147'', -118'') | 12 | —— | Plage | 3620104423 |
| Set 10 | 2014/01/07 | 13:44 | 14:38 | 167'' × 174'' | (-159'', -85'') | 19 | 11944 | Sunspot/Plage | 3860259472 |
| Set 11 | 2016/01/14 | 18:11 | 19:07 | 119'' × 119'' | (387'', 355'') | 11 | 12483 | Plage | 3600257420 |
| Set 12 | 2016/01/19 | 15:09 | 16:03 | 60'' × 65'' | (-18'', 313'') | 11 | 12485 | Plage | 3610257419 |

2 METHODS

2.1 Observations

The aim of this work is to analyse burst events with short lifetimes in the transition region of Active Regions (ARs) meaning high-cadence (≤20 s) in the Slit-Jaw Imager (SJI) 1400 Å channel is essential. Additionally, we require a near constant field-of-view (FOV) in order to analyse the entire lifetimes of bursts implying that data must have been recorded in either sit-and-stare mode (in which the IRIS slit is fixed at a particular location on the Sun and continuously tracks the solar rotation) or in dense raster mode with a maximum of four steps (~1'' shift in FOV). Searching the IRIS data catalogue with these criteria returned several hundred candidate datasets totaling tens of TB in size. However, as analysing all of these datasets was not possible at this time, here we focus instead on a smaller sample of 12 datasets in order to understand some general properties of bursts which can be used to infer interesting results and direct future research. The details of these 12 SJI datasets are presented in Table 1, where the stars indicate the five datasets which also include simultaneous imaging from the IRIS SJI 1330 Å channel. These data were downloaded as Level-2 IRIS data products, on which dark current removal, flat-field, geometrical distortion, orbital and thermal drift corrections had been applied.

The SJI 1400 Å channel is dominated by the Si iv 1394 Å and 1403 Å resonance lines which are formed in the transition region, while the SJI 1330 Å channel is dominated by the C ii 1335 Å and 1336 Å lines which are formed in the upper chromosphere. The mean formation temperature of C ii and Si iv lines are ~3 × 10^4 K and ~8 × 10^4 K respectively (Rathore & Carlsson 2015; Rathore et al. 2015). Therefore, these two SJI channels provide an opportunity to study the energetics of burst-like events in two different layers in the solar atmosphere. Numerous authors, e.g.
Figure 3. The effect of changing the intensity threshold from 3σ (left column) to 5σ (middle column) to 7σ (right column) above the background, for varying minimum areas, on the detection of impulsive bursts in Dataset 1 for the SJI 1400 Å (top row) and 1330 Å (bottom row) channels. The distribution of bursts with area >1, >2, >3 pixels are shown in black, red, blue respectively. The effects of the minimum area condition are most apparent at low energies (below approximately 10^{23} erg). The over-laid ‘number of events’ indicates the total number of events detected with the area >3 pix.

Ayles et al. (1995), have shown flux–flux relationships between transition region lines and the X-ray flux. This work was taken one step further by Bruner & McWhirter (1988) and Doyle (1996) who showed a linear relationship between the flux of transition region lines and coronal lines, and the total radiative losses; hence the Si iv 1394 Å line is a good proxy to estimate the radiative losses in the atmosphere.

Seven out of the twelve datasets were already binned with a pixel scale of 0.33″, whilst the pixel scale for the remaining observations were approximately 0.17″. In order to have consistent pixel scales in all datasets, all observations were binned to have a pixel scale of 0.33″ before the application of the detection algorithm. In Fig. 1, we show an example of a dataset selected for analysis here. This dataset (Set 1 from Table 1) sampled a sunspot within AR NOAA 11836 in sit-and-stare mode between 15:59:35 UT and 17:54:29 UT on 2013 August 31. Both 1330 Å and 1400 Å SJI images were recorded with a 12 s cadence and a pixel size of 0.17″. The exposure time for the SJI observations was 4 s. In panels (a) and (b), we plot the SJI 1400 Å and 1330 Å images of the AR sampled at 17:12:28 UT, respectively. Corresponding AIA 1600 Å and 193 Å images collected by the Solar Dynamics Observatory’s Atmospheric Imaging Assembly (SDO/AIA Lemen et al. 2012) instrument are shown in panel (c) and panel (d), respectively. The white box over-laid on panels (c) and (d) outlines the FOV of the IRIS SJI observation. The SJI data in Fig 1 clearly display the presence of the localised brightenings we aim to study here.

2.2 Burst Detection Algorithm

2.2.1 Burst selection:

Intensities in IRIS SJI data are stored in DN units, however, the exposure time of images may not be constant during the observation. In order to correct for this effect, intensity values were divided by the corresponding exposure times before these exposure normalised images were used for the detection of impulsive brightening events. Event selection was carried out by scanning the light curve of each pixel in the FOV. The algorithm starts by calculating the background intensity in each pixel from its time-series data before obtaining the standard deviation (σ) with respect to the background intensity. The algorithm first determines the minimum intensity of the pixel from its light curve and then calculates the average intensity of the light curve by excluding regions which are 5 times larger than the minimum intensity. This condition helps to remove impulsive brightening while calculating the background intensity. Impulsive bursts were then identified through the presence of intensity peaks which are significantly above background fluctuations for a user-defined time. We analysed the effects of varying the local intensity threshold between 3σ and 7σ as well as varying...
the minimum lifetime of bursts with these results being presented in
the later sections of this article. The minimum burst lifetime studied
was limited to three times the cadence in order to differentiate be-
tween bursts and cosmic ray spikes, which typically do not appear
at the same location in subsequent images.

We also applied a condition that the enhanced emission iden-
tified as a bursts should be at least twice the average intensity of
the entire FOV. A single pixel can have multiple bursts since there is a
possibility of having multiple intensity maxima at the same location
through time. As there could be some non-impulsive brightening
events in the FOV, an impulsivity criterion was applied to remove
sustained brightening events. For this, we calculated the average
enhancement in intensity during the burst and divided this value
by the background flux for that specific pixel. This ratio should be
greater than 1 to be considered as an impulsive event. As no algo-
orthy is perfect in detecting bursts, there is a possibility of exclud-
ing actual burst-like events as well as including non-burst regions.
Choosing the correct combinations of parameters and conditions
can minimise the mis-identification of the bursts.

2.2.2 Area and lifetime of the burst:

Once an impulsive burst was identified in a pixel, an iterative ap-
proach was then used to calculate the total area and lifetime of the
event. In the first step, the algorithm searched for connected pixels
with intensity above the user defined intensity threshold during the
peak time. Minimum area thresholding was applied within the al-
gorithm to reduce incorrect identifications, with limits of >1, >2,
or >3 pixels all studied. In the next step, the algorithm searched for
the impulsive events connected to the pixel in the previous time-
step. The bf algorithm continued this iteration until it reached a
time where there were no pixels above the intensity threshold. This
same iterative method was also applied forward in time. Using this
method, we were able to determine the starting time as well as the
ending time of the burst. In this approach, the total area of the burst
is a combination of all the spatially connected pixels throughout its
lifetime. Once a burst location and time was identified, we removed
these data points from the data cube to avoid multiple detections.

2.2.3 Energy determination:

Before calculating the energy of these impulsive events it is neces-
sary to express the SJI intensities in radiometric units, which pro-
vides the energy flux at the Sun. This can be done using the equa-
tion:

\[
\text{Flux (erg cm}^{-2}\text{s}^{-1}) = F (DN/s) \frac{4\pi E_{\lambda} k}{A \Omega}
\]

where \(E_{\lambda}\) is the energy of the photon and \(k\) is the factor that con-
verts the DN to the number of photons. This factor is the ratio be-
tween gain and yield. The gain is the number of electrons released
in the detector that yield 1 DN and the yield is the number of elec-
trons released by one incident photon. \(\Omega\) is the SJI pixel size in
steradian. \(A\) is the post-launch effective area calculated using the
‘iris_get_response.pro’ routine, which accounts for the degradation
of the instrument since launch. The time over which the energy was
calculated included the rise and decay phases of the bursts, deline-
ated by the times when the gradient of the pixel intensity was zero
before and after the burst. The energy radiated during the event
can be calculated by integrating the radiated energy flux in time,
in all bright pixels of each event. The background emission was
subtracted while calculating the energy of the burst.

2.3 Testing the detection algorithm

Before performing the detection on real SJI images, we tested the
detection algorithm on a synthetic dataset to verify its robustness.
Firstly, we created a data cube that has base intensities which fol-
low a Gaussian distribution. Since real solar data is not perfectly
Gaussian, we introduced asymmetry by multiplying each pixel by an
error function. Secondly, we scanned through the light curve of
each pixel to obtain the average background intensity and the back-
ground fluctuations. Thirdly, we randomly selected 100 locations in
the data cube using the IDL randomu function and increased the in-
tensity values in the corresponding locations by 10\(\sigma\) for a specified
lifetime. These enhanced intensity pixels represents the observed
bursts. Finally, we detected bursts with a minimum area of 3 pix-
els that are 3\(\sigma\) above the background and obtained the integrated
intensity enhancement.

The algorithm was successful in detecting simulated bursts; detec-
ting 98 bursts out of 100. The code failed to detect 2 bursts since
they were overlapping. In Fig. 2, we compare the intensity
enhancement integrated over the actual area and lifetime of the
bursts with the one obtained from the detected bursts. The inte-
grated intensity enhancement represents the energy of the burst,
which determines the power-law slope. Histograms for the actual
values of integrated intensity enhancement are shown in the top
panel of Fig 2 while the value determined from the detected bursts
is presented in the bottom panel. The similarity between these two
plots implies how successful is the detection algorithm in determin-
ing the energies of the bursts.

3 RESULTS

Initially, we tested the effects of the chosen intensity threshold and
minimum area conditions on the returned power-law indices. We
present results from Dataset 1 in Fig. 3, however, results from all
other datasets are included in Table 2. Some datasets do not have
the SJI 1330 Å channel, also for the short duration datasets we have
too few points to provide accurate estimates of the power-law in-
dex when using a minimum lifetime condition of 110 s. In the top
row of Fig 3, we plot radiative energy against frequency for burst
events detected in the SJI 1400 Å channel with a minimum lifetime
of 110 s, with the three panels representing varying intensi
thres-
olds. Similar results are plotted for the IRIS SJI 1330 Å channel in
the bottom panels. The intensity threshold used in the algorithm
are shown on the top of each panel, with the distribution of bursts
detected with enhancements of 3\(\sigma\), 5\(\sigma\), 7\(\sigma\) above the background
being shown in the left, middle, and right columns, respectively.
The colour of the distributions represent the minimum area condi-
tion applied while detecting impulsive events with areas of >1, >2
and >3 pixels being plotted in black, red, and blue, respectively.
Intuitively, more events are detected (especially at lower energies)
when lower intensity thresholds are applied. Notably, despite fewer
events being recorded, the maximum energies returned from the SJI
1330 Å channel are larger than those returned from the SJI 1400 Å
channel by up to an order of magnitude with some features having
energies > 10^{26} erg (see, for example, the middle panels of Fig. 3).

Here, the radiative energies of the detected impulsive events
range from 10^{22} erg to 10^{26} erg, thus these events could be consid-
ered to be nano-flares. At lower energies (< 10^{23} erg), the distribu-
tion of bursts fails to follow a power-law as the frequency of the de-
tected bursts decreases with decreasing energy. The drop-off from
the power law distribution at low energies is larger in bursts de-
tected with less stringent intensity thresholds (black curves). This
indicates that the drop off is likely to be caused by observational limitations (e.g., spatial and temporal resolutions) as it becomes increasing difficult to accurately determine the parameters of bursts that are near the detection limit of the instrument. It should be noted, however, that changes made in the distributions with varying minimum area conditions can only be seen in the lower energies with the blue curve being completely superimposed on the red and black curves at higher energies (> 10^{23} erg).

As the transition region of ARs are generally very dynamic in nature, we note that if we reduce the intensity threshold too far it is likely that fluctuations not associated with impulsive features will be counted as bursts. The above effect must be considered while calculating γ for the distribution from each dataset, meaning the power-law index was only calculated for energies above where the tail-off in frequencies are detected and for the most stringent area thresholding conditions (i.e., impulsive events with minimum area >3 pixels). For each of the intensity thresholds, the distribution displayed a clear linear behaviour on a logarithmic scale, with the resulting best fit and power-law index overlaid on each plot. Although the total number of events detected is reduced, as expected, with increasing sigma values, the γ-value remained stable within errors varying from 1.59 ± 0.05 (3σ) to 1.56 ± 0.08 (7σ) for the IRIS SJI 1400 Å channel and from 1.62 ± 0.08 (3σ) to 1.45 ± 0.11 (7σ) for the 1330 Å channel. This consistency gives us confidence in our results at higher energies.

In Table 2 we display how the power-law index varies when impulsive events are identified with intensity enhancements of 5σ and 3σ above the background and lifetimes of over either 110 s (second to fifth columns) or 60 s (sixth to ninth columns) for both the SJI 1400 Å and 1330 Å channels. For the 1400 Å channel with a minimum lifetime of 60 s, 4 (2) out of 12 (10) datasets have power-law indices above 2 for 3σ (5σ). With a minimum lifetime of 110 s this decreases to 3 (0) out of 10 (9) datasets. This result suggests that higher cadence data may return greater values of γ in general. For the 1330 Å channel (where only 5 datasets are available) these values are 1 (0) out of 5 for a minimum lifetime of 110 s and 2 (1) out of 5 for a minimum lifetime of 60 s. To display the accuracy of the power-law fitting, we plot three further examples (Datasets 3, 4, and 5) from the SJI 1400 Å line at the 3σ level with a minimum lifetime of 60 s and a minimum area of 3 pixels in Fig. 4.

Table 2. Power-law indices of the impulsive events detected in each dataset by defining bursts as peaks with intensity enhancement 5σ and 3σ above the background for ~ 110 s (second to fifth columns) and ~ 60 s (sixth to ninth columns). ‘N/A’ indicates too few events were returned to provide an accurate estimate of the power-law index.

| Data | Power-law (γ) 5σ above the background | Power-law (γ) 3σ above the background | Power-law (γ) 5σ above the background | Power-law (γ) 3σ above the background | Power-law (γ) 5σ above the background | Power-law (γ) 3σ above the background | Power-law (γ) 5σ above the background | Power-law (γ) 3σ above the background |
|------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|      | SJ 1400 | SJ 1330 | SJ 1400 | SJ 1330 | SJ 1400 | SJ 1330 | SJ 1400 | SJ 1330 |
|      |       |       |       |       |       |       |       |       |
| 110 s |       |       |       |       |       |       |       |       |
| Set 1 | 1.56 ± 0.08 | 1.56 ± 0.09 | 1.59 ± 0.05 | 1.62 ± 0.08 | 1.54 ± 0.05 | 1.68 ± 0.08 | 1.81 ± 0.04 | 1.66 ± 0.04 |
| Set 2 | 1.62 ± 0.04 | 1.36 ± 0.04 | 1.72 ± 0.03 | 1.57 ± 0.04 | 1.74 ± 0.02 | 1.59 ± 0.04 | 1.96 ± 0.02 | 1.81 ± 0.02 |
| Set 3 | 1.71 ± 0.04 | 1.55 ± 0.06 | 1.89 ± 0.03 | 1.74 ± 0.05 | 2.01 ± 0.03 | 1.71 ± 0.04 | 2.03 ± 0.02 | 1.99 ± 0.03 |
| Set 4 | 1.85 ± 0.21 | 1.77 ± 0.25 | 2.08 ± 0.09 | 2.04 ± 0.12 | 2.07 ± 0.13 | 2.10 ± 0.15 | 2.27 ± 0.04 | 2.21 ± 0.05 |
| Set 5 | 1.79 ± 0.14 | 1.51 ± 0.21 | 2.03 ± 0.10 | 1.90 ± 0.11 | 1.90 ± 0.10 | 1.93 ± 0.16 | 2.20 ± 0.06 | 2.25 ± 0.08 |
| Set 6 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | 1.62 ± 0.20 |
|      |       |       |       |       |       |       |       | 1.75 ± 0.31 |
| Set 7 | 1.83 ± 0.02 | 1.83 ± 0.03 | 1.90 ± 0.02 | 1.91 ± 0.02 | 1.94 ± 0.03 | 1.94 ± 0.02 | N/A | N/A |
| Set 8 | 1.93 ± 0.03 | 1.82 ± 0.02 | 1.94 ± 0.03 | 1.94 ± 0.02 | N/A | N/A | N/A | N/A |
| Set 9 | 1.63 ± 0.07 | 1.76 ± 0.04 | 1.78 ± 0.04 | 1.98 ± 0.02 | N/A | N/A | N/A | N/A |
| Set 10 | 1.89 ± 0.16 | 2.06 ± 0.12 | 1.97 ± 0.07 | 2.03 ± 0.05 | N/A | N/A | N/A | N/A |
| Set 11 | N/A | 1.36 ± 0.15 | N/A | N/A | N/A | N/A | N/A | N/A |
| Set 12 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

Figure 4. Power-law distributions of impulsive events detected in the SJI 1400 channel with intensity enhancements above 3σ, minimum areas of >3 pixels and minimum lifetimes of 60 s for Datasets 3, 4, & 5.
Our results also indicate that the type of solar structures within the selected region (e.g., sunspot or plage) influences the power-law index. For regions dominated by sunspots, we always find that $\gamma < 2$ for all threshold values when minimum lifetimes of 110 s and 60 s are considered; however, when the FOV is dominated by plage regions, the $\gamma$ values are higher, with 3 out of 8 completely plage datasets (see Tables 1 and 2) having $\gamma > 2$ in the SJI 1400 Å channel at the 3$\sigma$ level for both 110 s and 60 s cadences. We present results obtained from one plage region in more detail in Fig. 5. In the top row of Fig. 5, we plot an overview of the FOV as sampled by the SJI 1400 Å channel (left panel), the AIA 1600 Å channel (middle panel), and the AIA 193 Å channel (right panel). Large amounts of plage are evident but no sunspots or pores are present. Having examined the effects of the intensity threshold, minimum area, and solar structures within the FOV, we now move on to further investigate how the minimum lifetime criterion influences the returned $\gamma$-values.

Two datasets which sampled the plage region plotted in the top row of Fig. 5 were studied here, with both datasets being sampled at different cadences (Datasets 6 with 5 s and Dataset 7 with 3
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for the remaining datasets. All but three datasets return
Bruner & McWhirter 
from each dataset. The total power per unit area of each impul-
γ > (s)

erve event from the SJI 1400 Å emission, $P = \int f(E)E dE = f_0 (E_{\text{max}}/E_{\text{min}}) \cdot E^{-\gamma}$, (2)
where $f_0$ is the normalization factor which can be calculated from the y-intercept of the energy distribution. $E_{\text{max}}$ and $E_{\text{min}}$ represent the observed minimum and maximum energy of the impulsive events from any given dataset.

In order to calculate the total energy of the bursts we must first estimate the Si iv 1394 Å emission. This can be done from the SJI 1400 Å channel by multiplying the burst energy obtained using our algorithm by 0.6 (i.e., assuming that around the ~ 60% of the SJI 1400 Å intensity is contributed by Si iv 1394 Å emission; Hansteen et al. 2014). Once the Si iv 1394 Å emission had been estimated, we calculated the total radiative power ($P_{\text{tot}}$) per unit area using the equation:

$\log(P_{\text{tot}}) = 2.69 + 1.08 \log(P_{\text{int}})$. (3)

This is based on work by Bruner & McWhirter (1988) and Doyle (1996) who produced emission measure distributions for different solar regions (active regions, coronal holes, sunspots, ‘quiescent’

regions and flares) plus a range of late-type stars based on data from the Hubble Space Telescope’s International Ultraviolet Explorer and found a linear correlation between the total radiative output and that from a single spectral line. The typical error is ±40% (Bruner & McWhirter 1988). The details of this calculation and the total radiative power obtained for all datasets is shown in Table 3. The derived values are typically only 10 – 25% of what is required in thermal energy to sustain the corona. If we were to extend the power-law distributions down to an energy of $10^{21}$ erg (as given in the final column in Table 3), and assume parity between the radiative energies reported here and thermal energy released by the impulsive events, then we would have approximately 25 – 50% of the required energy input to account for coronal heating.

Finally, we attempt to provide a more general answer as to the power-law index of these impulsive bursts in solar Active Regions. In order to do this we combined all of the datasets studied here in two ways. The first method combined the results obtained from each dataset when applying a minimum event lifetime of 60 s. The second method only considered datasets which facilitated a minimum lifetime condition of less than approximately 35 s. The intensity threshold was set to 3σ and the area threshold was set to > 3 pixels for both of these methods. In the top panel of Fig. 6, the derived distribution from the first method is plotted. The noise within the data is extremely low, however, the power-law index is well below 2. When only datasets which could allow us to probe events with sub-minute lifetimes were studied, the power-law index increased such that $\gamma > 2$. This result indicates that the analysis of extremely high-cadence IRIS SJI 1400 Å data in the future may provide further in-sights into the energy input into the outer atmosphere from small-scale impulsive bursts.

### 4 DISCUSSION & SUMMARY

In this article, we have studied the effects of minimum area conditions, temporal resolution, intensity thresholding, and structuring within a FOV on the returned power-law indices of distributions of impulsive brightening events in the transition regions of solar ARs. We have studied 12 IRIS SJI datasets (detailed in Table 1) using the automated detection algorithm described in Sect. 2. Our results indicate that the minimum area condition has a limited influence on the power-law index, with the main effect of decreasing the minimum area being that one is able to observe lower energy
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Figure 6. Combined energy distribution of all 12 datasets using a cadence of ∼60 s (top panel). Combined energy distribution from all data sets studied with a cadence of less than ∼35 s, i.e., for Datasets 1, 4, 6, 7, 8, 9, 11 & 12 (bottom panel).

In all of the regions studied, instrument sensitivity has a major impact on the detections at lower energies. Mondal et al. (2020) recently used the Murchison Widefield Array to observe the quiet Sun at radio frequencies. They detected impulsive emission with flux densities of about two orders of magnitude lower than the earlier attempts (a few mSFU where a Solar Flux Unit is 10−19 erg s−1 cm−2 Hz−1). These impulsive events have duration of ∼1 s and are present throughout the quiet solar corona. The estimate of the energy which must be dumped in the corona to generate these impulsive events is consistent with that required for coronal heating. In the events studied by these authors, the power-law indices were all >2. Combining this with our analysis implies that high cadence is an essential requirement for future analyses. In the future, the highest cadence IRIS SJI datasets available should be analysed in order to better understand the presence of impulsive brightenings at the smallest energy scales.

The Spectral Imaging of the Coronal Environment (SPICE) instrument on-board Solar Orbiter will observe a range of ultraviolet lines, the strongest being O vi 1031.9 Å with an estimated 8000 photons pixel−1 s−1 in an active region (Anderson et al. 2019). This would allow confirmation that brightening events from plage regions can account for the heating of the corona. Another up-coming facility is the Daniel K. Inouye Solar Telescope (DKIST) which will have a spatial resolution a factor of three better than currently available in the lower solar atmosphere. In the photosphere/lower chromosphere, Reid et al. (2016) analysed EBs observed in Hα profiles recorded by the Swedish Solar Telescope (Scharmer et al. 2003) using automated methods. These observation also took place in ARs, therefore, it is possible to compare their statistics with the impulsive brightenings detected in the upper atmosphere of the AR. The energies of the EBs ranged from 1021 erg to 1026 erg. The power-law index obtained for energies of the EBs was 1.67. Nelson et al. (2013) also looked at brightenings in the Hα line with the Dunn Solar Telescope but reduced the required intensity enhancement thereby detecting many more impulsive events. The radiative energy covered was from 2 × 1022 to 4 × 1023 erg with a slope of 2.14. Both of these power-law indices are comparable to those found here for a range of datasets. With the improved spatial resolution offered by DKIST, we will be able to resolve very small scale flaring events.

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**DATA AVAILABILITY**

The datasets were derived from sources in the public domain: [IRIS; https://iris.lmsal.com/, AIA; http://jsoc.stanford.edu/].

**REFERENCES**

Alfvén H., 1947, *MNRAS*, 107, 211
Anderson M., et al., 2019, arXiv e-prints, p. arXiv:1909.01183
Antiochos S. K., Karpen J. T., DeLuca E. E., Golub L., Hamilton P., 2003, *ApJ*, 590, 547
Aschwanden M. J., Parnell C. E., 2002, *ApJ*, 572, 1048
Ayres T. R., et al., 1995, *ApJS*, 96, 223
Bowell R., Hood A. W., Parnell C. E., 2013, *A&A*, 560, A89
Brueckner G. E., Bartoe J. D. F., 1983, *ApJ*, 272, 329
Brunner M. E., McWhirter R. W. P., 1988, *ApJ*, 326, 1002
Cargill P. J., Klimchuk J. A., 2004, *ApJ*, 605, 911
De Pontieu B., et al., 2014, *Sol. Phys.*, 289, 2733
Doyle J. G., 1996, *A&A*, 307, 162
Doyle J. G., Butler C. J., 1985, *Nature*, 313, 378
Ellerman F., 1917, *ApJ*, 46, 298
Golub L., et al., 1999, *Physics of Plasmas*, 6, 2205
Graham D. R., De Pontieu B., Testa P., 2019, *ApJ*, 880, L12
Hansteen V., et al., 2014, *Science*, 346, 1255757
Huang Z., Madjarska M. S., Scullion E. M., Xia L. D., Doyle J. G., Ray T., 2017, *MNRAS*, 464, 1753
Huang Z., et al., 2018, *ApJ*, 854, 80
Hudson H. S., 1991, *Sol. Phys.*, 133, 357
Jess D. B., et al., 2019, *ApJ*, 871, 133
Krucker S., Benz A. O., 1998, *ApJ*, 501, L213
Lemen J. R., et al., 2012, *Sol. Phys.*, 275, 17
Levine R. H., 1974, *ApJ*, 190, 457
Mondal S., Oberoi D., Mohan A., 2020, arXiv e-prints, p. arXiv:2004.04399
Nelson C. J., Doyle J. G., Erdélyi R., Huang Z., Madjarska M. S., Mathioudakis M., Mumford S. J., Reardon K., 2013, *Sol. Phys.*, 283, 307
Nelson C. J., Scullion E. M., Doyle J. G., Freij N., Erdélyi R., 2015, *ApJ*, 798, 19
Nelson C. J., Doyle J. G., Erdélyi R., 2016, *MNRAS*, 463, 2190
Nelson C. J., Freij N., Reid A., Oliver R., Mathioudakis M., Erdélyi R., 2017, *ApJ*, 845, 16
Parker E. N., 1988, *ApJ*, 330, 474
Parnell C. E., Jupp P. E., 2000, *ApJ*, 529, 554
Parnell C. E., Maclean R. C., Haynes A. L., 2010, *ApJ*, 725, L214
Peter H., et al., 2014, *Science*, 346, 1255726
Rappazzo A. F., Velli M., Einaudi G., Dahlburg R. B., 2008, *ApJ*, 677, 1348
Rathore B., Carlsson M., 2015, *ApJ*, 811, 80
Rathore B., Carlsson M., Lemen J. R., De Pontieu B., 2015, *ApJ*, 811, 81
Reid A., Mathioudakis M., Doyle J. G., Scullion E., Nelson C. J., Henriques V., Ray T., 2016, *ApJ*, 823, 110
Rouppe van der Voort L. H. M., Rutten R. J., Vissers G. J. M., 2016, *A&A*, 592, A100
Scharmer G. B., Bjelksjo K., Korhonen T. K., Lindberg B., Petterson B., 2003, The 1-meter Swedish solar telescope. pp 341–350, doi:10.1117/12.460377
Shimizu T., 1995, *PASJ*, 47, 251
Testa P., et al., 2013, *ApJ*, 770, L1

Withbroe G. L., Noyes R. W., 1977, *ARA&A*, 15, 363
Young P. R., et al., 2018, *Space Sci. Rev.*, 214, 120

Vissers G. J. M., Rouppe van der Voort L. H. M., Rutten R. J., 2013, *ApJ*, 774, 32

MNRAS 000, 000–000 (0000)