



Solo campfires in SDO images

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Abstract. I present the appearance of “Solar Orbiter campfires” in simultaneous images from the Solar Dynamics Observatory where most are visible although less sharp. I also show such features elsewhere in the SDO database. I show some in detail and discuss their nature.

Contents

1	Introduction	1
2	Finding Solo campfires	2
3	SDO data collection	2
4	Solo–SDO scene	3
5	Campfires in other SDO scenes	3
6	Solo–SDO campfire cutouts	4
7	Solo–SDO brushfire cutouts	6
8	Discussion	6
	Campfire nature	6
	Quiet-Sun heating	7
	Campfire prospects	8
9	Conclusion	8
A	AIA 1600 and 1700 Å comparison	9
	EBs and FAFs	9
	EBFAF movies	10
	EBDETECT	10
	FAFDETECT	10
	AIA 1600/1700 with limbshift correction	10
	MCs in AIA 1600 and 1700 Å	10
B	AIA 304 Å and GONG Hα comparison	11
	Chromosphere in H α and He II 304 Å	11
	Dark in H α versus bright in He II 304 Å	12
	Non-E fibril canopies in H α and He II 304 Å	12
	Chromosphere in AIA 131 Å	12
	Chromosphere around quiet network	13
	Dark EUV features	13
	Chromosphere under brushfires	13
	He II 304 Å in a well-sampled brushfire	14
C	Epilogue on publishing	14
	Acknowledgments	15
	Version history	15
	References	15
	Figures	18
	List	18
	Figure blinking by page flipping	18
	Solo press-release image	19
	SDO Solo field	20
	SDO other-field triples	35
	SDO campfire ROI cutouts	65
	SDO brushfire ROI cutouts	79
	SDO ROI locations and fire detector	84
	Appendix A	88
	Appendix B	92

1. Introduction

On July 16, 2020 a friend with interest in science alerted me to an on-line ESA–NASA press conference that afternoon to announce first images from Solar Orbiter (SoLO): “closer than ever before”.

I had not expected this so soon after launch, but found a [video movie](#) of the ecliptic-projected orbit and saw that SoLO dropped behind Earth so much at launch that it fell considerably from Earth orbit towards this relatively close pass (0.5 AU) then all-ready.

A newspaper journalist then informed me embargoedly that the press release would boast “many little flames”.

Naturally I speculated about familiar solar little-flame phenomena: Ellerman bombs (EB, [Rutten et al. 2013](#)), quiet-Sun Ellerman-like brightenings (QSEB, [Roupe van der Voort et al. 2016](#)), flaring active-region fibrils (FAF, [Rutten 2016](#)), IRIS bombs (IB, [Peter et al. 2014](#)), UV bursts ([Young et al. 2018](#)), tips of spicules-II in on-disk appearance as rapid blue excursion (RBE, [Langangen et al. 2008](#)) or rapid red excursion (RRE, [Sekse et al. 2013b](#)), and (ALMA) mm bursts ([da Silva Santos et al. 2020](#)).

Attending the press conference made clear that the little flames, coyly called “campfires”, sat in images from the EUV 174 Å HRI telescope implying million-K temperature and hence excluding EBs and QSEBs since these reconnection flames remain photospheric, not reaching EUV temperatures and even not breaking through the H α fibril canopy (which also hides them for ALMA, [Rutten 2017b](#)).

The tips of RBEs and RREs do reach out of the canopy and often reach EUV temperatures ([Henriques et al. 2016](#)), but these occur ubiquitously around network including quiet unipolar network, much less scarce than the dozen or so campfires in the approximately $0.5 \times 0.5 R_{\text{Sun}}$ Solo image that was shown.

The Solo campfires looked like FAFs to me.

I have inspected many FAFs in specific EBFAF detection movies multiplying SDO/AIA 1700 Å and 1600 Å after normalization, but the only detailed FAF descriptions are in [Vissers et al. \(2015\)](#). More in [appendix A](#).

Here I report on my eventual finding these SoLO campfires in SDO images. To cut the long story short: they are not FAFs. I speculate what instead.

The contents table serves as clickable outline; I therefore refrain from adding a descriptive contents outline here.

I keep the figures at the end to facilitate parallel text and figure inspection using a second pdf-reader instance (or printing the text if you prefer paper). For many images zoom-in to detail may be useful. Most are full-page to enable blinking by page flipping ([how-to per viewer](#)).

2. Finding SoLO campfires

Immediately after the press conference I shared my FAF suspicion and asked whether the images would be public and whether I might have access to them for checking per SDO with my EBFAF detection technique. The quick answer from EUI PI David Berghmans was “yes” – but that it would take some months.

For a first look, being curious and impatient, I therefore saved the press-release high-resolution 174 Å image ([figure 1](#)), noting that the others shown were cutouts of it, asked for information where on the Sun and when it was taken, and downloaded the SDO/AIA 171 Å daily movie for the stipulated May 30, 2020 date to locate the SoLO image scene.

The SoLO EUI/HRI telescopes have 2048×2048 0.5 arcsec pixels, the same angular pixel size as SDO/HMI (4096×4096) and TRACE (1025×1024) and close to the 0.6 arcsec of the four SDO/AIA telescopes to which SSW’s `aia_prep.pro` rescales HMI products. Hence, from about 0.5 AU the campfires should be twice sharper with SoLO, but since they extend multiple pixels in the press-release image they should be visible in AIA 171 Å also.

The orbit movie suggested that SoLO was about 40 degrees in advance of the Earth along the ecliptic, so I concentrated on pattern recognition of the SoLO scene in [figure 1](#) towards the West limb in the AIA 171 Å movie, hoping that the EUI/HRI telescope pointed near sub-SoLO disk center and not towards the SoLO West limb where the scene would already be backside for SDO.¹

I did not find the scene, also not for SoLO’s full-disk 304 Å images in the press release.

I got no answer on my when and where question² and I also realized that the SoLO image might have been taken anywhere on the Sun with any orientation, perhaps even flipped or mirrored, and possibly beyond the SDO limb. Then Greg Slater (LMSAL) pointed out that the zoom movie shown in the press conference morphed between unrelated, disjoint scenes and so could not be used in location finding; the 304 Å full-disk view I had taken as guide might be from another date and have other orientation. He also suggested that the high-resolution image might have been

¹ And for IRIS, Hinode, SST etc. if co-pointing had been requested – which I hoped since multi-telescope multi-diagnostic observation is the proper way to do solar physics in my view, motivating my efforts in SDO–other telescope co-alignment and before that in running [EU networks](#).

² Nor a reaction on this report although I shared a link while writing it. The admonition now under [figure 1](#) came only post-posting. The current live link is [this website post](#) updating the [arXiv post](#) and also retaining an [epilogue \(pdf 14\)](#) on starting this report series.

taken during June at yet smaller SoLO distance to the Sun but increasing SoLO–Earth sight-line difference.

I therefore collected daily SDO 171 Å movies for many days and played them endlessly against the SoLO image in diverse orientations, trying visual pattern recognition – very confusing, the proverbial needle in a haystack. After many days of increasing frustration I gave up.

Eventually, on July 28 ESA mission scientist Daniel Müller informed me that the image was actually taken on May 30 as stipulated, around 14:54 UT. This enabled full-resolution full-cadence full-disk AIA sequence downloads and inspection at more detail than the SDO daily movies.

It took me a few days more but then I finally recognized the SoLO scene in SDO 171 Å. After all my far-too-wide casting I found that the image was actually taken somewhat east of sub-SoLO disk center, not flipped or mirrored, and had only small-angle rotation from solar North up as seen from the Earth and SDO.

3. SDO data collection

Over the past decade I developed an extensive IDL pipeline to cross-align JSOC “`im_patch`” cutouts precisely between all SDO diagnostics and then co-align the results with small fields from other telescopes, in particular the Swedish 1-m Solar Telescope (SST). The first part is used here.

I aim to present this pipeline in another report in this series, but some detail is given already in my brief manual in the IDL directory where I make this software available.³

In a nutshell, a single call of `sdo_getdata.pro` requests, collects, and cross-aligns SDO cutouts from JSOC, small ones at full cadence for the target area and large ones at lower cadence around disk center. The latter are used to find spatial offsets between the SDO diagnostics (“channels”) by cross-correlation of many small subfields, usually 30×30 arcsec each, applying apparent height-of-formation differences and iterative outlier removals, as function of time during the requested sequence duration. Examples before and after are shown in [figure 75](#). These “driftscenter” results are stored and used for the target cutouts, usually yielding cutout cross-alignment precision about 0.1 arcsec (an order better than the start-off co-registration by `aia_prep.pro`).

With `sdo_getdata_rr, '2020.05.30_14:50', 15, 375, 148, xsize=700, ysize=700` I targeted a wider area around the SoLO field during 15 minutes. The program took 42 min⁴ to deliver the material used here.

In visual comparison I found that the best match with the SoLO image in [figure 1](#) occurred around time step 46 or 14:58:46 UT.

In addition I made full-disk images and charts at this best-match time with my `sdo_diskfigs.pro` which may be used for any non-eclipsed SDO moment and includes optional GONG H α download. It yielded the full-disk SDO overviews in [figures 2–6](#) with the JSOC target cutout outlined.

There were two minor active regions near the East limb. The outlined SoLO target shows nothing active beyond quiet network on the surface, but diffuse and also concentrated patches of EUV brightness – formerly “bright points” but “fires” now.

³ https://webspacescience.uu.nl/~rutte101/Recipes_IDL.html

⁴ Deep Thought computation.

Normally, I obtain precise co-alignment with the “other” telescope (called STX for Solar Telescope X in my [software](#) and [manual](#)) which includes removal of small SDO wobbles left over from the JSOC whole-pixel cutout selection. Precise pixel-by-pixel SDO–STX comparisons are then possible and easily done with my versatile [showex.pro](#)⁵ sequence browser and blinker which can load very many different files and also cube parameters in memory together with jpg images or mpg movies and then zoom-in to pixel level.

In this case, however, I could not use my [sdo_stx_align.pro](#) because the SDO scene is foreshortened by its limbward viewing, differential across its large field, with respect to the Solo scene nearer disk center (probably with opposite foreshortening).

No pixel-by-pixel co-registration therefore, but it was easy to manually co-locate Solo campfires and larger “brushfires”⁶ precisely in SDO/AIA images with [showex](#) and then zoom-in to pixel detail to obtain pixel-clicked joint location output for matching ROI = “region of interest” cutouts of the Solo image and the SDO images.

These double coordinate pairs became the cutout centers for the 17 ROI cutout assemblies shown in [figures 47–69](#). Their fields are sufficiently small to permit de-foreshortening and height-difference corrections detailed below.

4. Solo–SDO scene

[Figure 1](#) shows the Solo press-release high-resolution image from the 174 Å EUV HRI telescope.⁷ I see about a dozen campfires in subjective selection of tiny bright features. The 2048×2048 px image measures about 402×402 Mm² on the Sun, suggesting campfire density about 10⁻⁴ Mm⁻² or less than a thousand on the Sun if the remaining surface – in this quiet cycle phase – shows them likewise. Too scarce for a significant role in coronal heating.

[Figures 7–15](#) show corresponding but somewhat larger SDO cutouts (plus a GONG H α cutout) at the best-match time in a selection that is diagnostically ordered bottom-to-top or cool-to-hot in naïve interpretation. The axes specify standard solar (X, Y) coordinates with the origin at sub-Earth disk center, Y pointing to the solar North pole, in arcsec⁸. For each SDO image the greyscaling is defined by the entire 15-min downloaded sequence to obtain common greyscales per diagnostic for the ROI cutouts in [figures 48–65](#).

IDL [showex](#) inspection with zoom-in and blinking is the best method for detailed comparison of these image sequences; the reader may do so by installing my pipeline, duplicate the above [sdo_getdata](#) command and inspect with [showex](#). Flipping the below figure pages is a poor blinking emulation; zoom-in to de-

⁵ The underlying engine is [movex.pro](#), built on SSW’s [ximovie.pro](#) written by Øyvind Wikstøl and Viggo Hansteen for pre-Hinode *Solar-B*.

⁶ Ron Moore corrected my English by writing “brushfire” in a reaction on the first arXiv version. I had used “bushfire” for a fire larger than a “campfire” but smaller than “burning prairie” (obviously sardonic), but I did not appreciate that “bushfire” is Australian dialect for any wildfire including giant forest fires. Since then I call the larger-than-campfire fires “brushfire”. From the third arXiv version I call campfires “St. Elmo’s fire”.

⁷ The Solo/HRI pixels are 0.5 arcsec just as for SDO/HMI but twice smaller in km on the Sun at 0.5 AU distance. I could not add (X, Y) axes to [figure 1](#) because I do not know the sub-Solo XCEN and YCEN pointing values nor the precise pixel size and image orientation. The derotation applied here is a visual estimate.

⁸ Here called “SDO arcsec” for viewing from Earth.

tail is emulated as poorly in the ROI cutout assemblies in [figures 48–65](#).

Unfortunately, the Solo image cannot be blinked at the pixel level to the SDO ones due to the considerable morphing by different and varying foreshortening. This also inhibits scatter correlations with Strous diagrams defined in [Section 2 \(pdf 2\)](#)⁹ of [Rutten et al. \(2019\)](#) and used here in [figure 74](#).

Visual comparison with [figure 1](#) shows that many campfires are also visible in the hotter AIA diagnostics, not only in AIA 171 Å ([figure 14](#)). In AIA 193 Å ([figure 15](#)) especially in dark areas where they stand out clearer.

Upshot: Solo was not required for noticing these small flames, although it does show them better. The gratifying good news is that the EUV HRI 174 Å telescope functions well.¹⁰

The Solo image appears clipped at the brightest levels. I therefore made the histograms in [figure 16](#). The Solo histogram shows no sign of clipping but an extended highest-brightness tail not present in the AIA 171 Å histogram. I therefore added “cooler” and “hotter” AIA 131 and 193 Å histograms. The latter shows a similar tail, suggesting either nonlinear response in the Solo image or that its 174 Å bandpass includes hotter contributions than AIA’s 171 Å bandpass. The visibility of many Solo campfires in [figure 15](#) suggests the latter.

5. Campfires in other SDO scenes

Obviously the next question is whether the area imaged by Solo was somehow fortuitously special and lucky in uniquely harboring campfires not visible anywhere else or anytime before. The press release claimed “omnipresent miniature solar flares” but showed only the field of [figure 1](#).

I therefore repeated [sdo_getdata](#) sequence collection and processing again for the best-match time but at sign-reversed X and/or Y to sample all four disk quadrants likewise, and also for the Solo pointing at the same date and time in the past three years. [Figures 17–34](#) show the results. They are combined in “triples” per location, arranged for easy blinking by page flipping ([how-to viewer hints](#)).

The first figure in each triple is the AIA 193 Å image, selecting this wavelength because it shows Solo campfires clearest of [figures 7–15](#).

The second per triple shows my “SDO fire detector” construct to detect campfires and brushfires distinct from more ubiquitous chromospheric heating. It was inspired by EBFAD detection ([appendix A](#)) and [figure 74](#) and proved useful in [figure 69](#) of which the caption describes the construction. The greyscale clip and color threshold are defined for quiet network.

The detector construct appears to supply an amazingly good spatial separator between chromospheric heating and coronal heating in quiet-Sun regions. Chromospheric heating shows up as

⁹ Direct pdf page links as this one open the cited page on your screen with all pdf viewers I know – but not reliably under macOS. Mac users may instead be shunted to the first page and must then manually find the cited page. For the Mac-challenged I add the pdf page number in these links. Acrobat may require undoing security settings disabling the opening of web pages.

¹⁰ Just as the granulation and magnetic bright points in the press-released first DKIST images show nothing not already known from e.g., SST imaging, but do demonstrate promising telescope functioning. But also the same story – for lack of asked-for pointing information I did not find their scene in HMI images.

ubiquitous grey network patches, similarly present nearly everywhere. Coronal heating shows up as sparser small campfires and larger loop-bundle brushfires of which the cyan detector pixels emphasize the feet. More diffuse coronal heating with large-scale connectivity seen in 193 Å spreads around brushfires and may well be caused by these or preceding instances.

The third per triple shows the corresponding HMI magnetogram, clipped as described in the caption of [figure 7](#).

Triple blinking is best done pairwise: 193 Å – detector and detector – magnetogram.

Blinking 193 Å – detector pairs in [figures 17–34](#) shows that the detector does a good job in locating small campfires. Some of these fields contained active regions around which the thick haze of extended coronal loops in 193 Å hides small fires underneath, but the detector unveils some. Elsewhere the 193 Å and detector images in these six other-scene triples display similar tiny campfires at roughly similar (scarce) density as in [figures 1](#) and [69](#).

Upshot: campfires seem indeed a sparse but omnipresent solar phenomenon. If SoLO had been targeted elsewhere or launched earlier we would have had the same press conference.

Blinking detector – magnetogram pairs in [figures 17–34](#) shows directly and unequivocally that all larger brushfires are located above or between mixed-polarity patches of multiple MCs (magnetic concentrations), suggesting EUV-visible heating due to bipolar MC happenings on the surface. All lie in extended grey patches in the detector images that represent dynamically heated chromosphere above and around network including “quiet” network ([appendix B](#)).

Only the smallest campfires seem to not always share bipolar magnetic feet (at HMI resolution and sensitivity), but these still lie preferentially in heated-chromosphere network patches.

Blinking 193 Å – detector pairs shows nearly 1:1 correspondence between campfire presence in 193 Å and cyan detector pixels, suggesting common heating to lower and higher temperatures.

The larger brushfires generally consist of close-packed short bright arches in 193 Å that connect opposite-polarity MC clusters in the magnetograms. In many the corresponding cyan detector pixels are grouped at the arch feet.

The campfires generally differ from the brushfires by not showing multiple-arch topography but just small single flames.

Another difference lies in their time behavior seen in `showex` viewing each downloaded time sequence: the campfire flames appear momentarily, mostly without repeat at the same location, whereas the brushfires live longer, usually throughout these 20-min sequence durations.

I also collected long-duration SDO sequences following the SoLO scene six hours before and six hours after the SoLO moment and found that most brushfire sites kept brushfiring continuously, irregularly but generally present during this time span.

The next question is whether campfires are a global quiet-Sun phenomenon still present during minima, or instead an activity phenomenon restricted to the activity belts and occurring with cycle modulation.

I therefore repeated `sdo_getdata` sequence collection and processing for similar-size North-pole and South-pole target areas during the maximum of cycle 24 and during the subsequent present minimum. [Figures 35–46](#) show the results, again

grouped together in 193 Å – detector – magnetogram triples for pairwise blinking.

These four polar areas also show campfires in quiet areas, including polar holes. Blinking 193 Å – detector pairs suggests that the smaller ones lie roughly as deep in the atmosphere in these diagnostics: they jump less limbward than the hazier 193 Å protrusions above them. I tried `heightdiff = 1000 km` for their construction ([appendix A](#)) but it made no difference in fire detection. Campfires are a chromospheric phenomenon¹¹.

The North-pole at maximum in [figure 36](#) shows fewer fires towards the limb than the others – but there may be blocking along slanted lines-of sight to deep-lying fires, more at larger activity. Overall campfires seem a global phenomenon.

Blinking detector – magnetogram polar pairs shows increasing limbward offsets, to the extent that near the limb fires and MC patterns are hard to match. Expected since the average height of the 304 Å chromosphere is multiple thousands of km, translating to projected shifts of multiple arcseconds there.¹²

Thus, campfires lie relatively deep for EUV phenomena, but not below the chromosphere as photospheric EBs and QSEBs do. The same holds for brushfire feet.

The ten-year full-disk high-cadence SDO database potentially permits an immensely rich harvest of campfires and brushfires, including appearance in other diagnostics as in these triples and also scene evolution before and after as in the ROI figures below. The fire detector offers an easy way to find SDO fires. The first projects suggested in [section 9](#) are obvious strategies to elaborate on these few first-look trial samples shown here.

However, the 20 blink pairs of this section already furnish a vivid tell-tale overview of fire occurrence and properties. The tentative conclusion is that all or nearly all fires represent small-scale heating caused by bipolar MC interactions on the surface, likely occurring as globally as somewhat active mixed-polarity network does.

The larger, i.e., brushfires, clearly heat the corona locally above them and possibly elsewhere via long-loop connectivity. The smallest, i.e., campfires, are located at chromosphere heights and appear to not contribute wider coronal heating.

Chromosphere heating (of the ubiquitous grey network patches in the detector images, see [appendix B](#)) is instead wide-spread and not due to fires.

The next sections enlarge fires in the SoLO field of [figure 1](#) for more detailed inspection.

6. SoLO–SDO campfire cutouts

[Figures 48–59](#) compare ROI = “region of interest” cutouts of SoLO 174 Å campfires and corresponding co-located SDO diag-

¹¹ Qua height, but not qua Lockyer (1868) since not seen in H α . This can be checked at SST resolution by working through my [school demo](#) of my SDO co-alignment pipeline.

¹² My pipeline presently uses limb value `heightdiff = 3600 km` for AIA 304 Å to HMI magnetogram cross-alignment, twice as much as in plane-parallel standard models but likely on the small side. An unpublished limb spectrum taken early in the IRIS mission by Bart De Pontieu and reduced by Han Uitenbroek shows Mg II h & k sticking out beyond 5000 km, whereas Mg II ionizes away at temperature 20 kK (coronal equilibrium) or lower (Saha-Boltzmann) about where He II comes up, so should appear “below” or near that unless non-E applies ([appendix B](#)). See also [Alissandrakis \(2019\)](#).

nostics. These cutouts measure 24×24 arcsec. [Figure 47](#) shows their locations in the $\text{SoLO } 174 \text{ \AA}$ image.

The SDO cutout panels are de-foreshortened to mitigate slanted limbward viewing. This means that the original cutout pixels, which sample compressed solar surface in the limb direction with respect to transverse and at sub-SDO disk center, are increased in number in the limbward direction to stretch the surface they sample to the extent they would have in sub-SDO viewing from above.¹³

Since I do not know the sub- $\text{SoLO } (X, Y)$ pointing I cannot apply deforeshortening to the SoLO cutout at the top of these ROI figures. It is likely less but opposite.

The de-foreshortened SDO cutouts are ordered in time-delay columns, respectively 5, 2 and 1 min before the best-match time and then 1, 2, and 5 min later. These samplings emulate *showex* time-sliding while blinking.

From bottom to top the diagnostic order is as for [figures 7–15](#), but adding the HMI continuum showing granulation at the bottom and replacing $\text{AIA } 1600 \text{ \AA}$ with a construct called 16001700 and based on the $1600/1700 \text{ \AA}$ ratio to display excess $\text{AIA } 1600 \text{ \AA}$ brightenings.

I switched to this construct instead of my usual EBAF detection described in [appendix A](#) when I saw the scene in the AIA images. I would not have made my FAF suggestion if I had immediately been able to inspect SDO UV images for the correct date, time and disk location. When I finally could do so with [figures 8–9](#) I saw no indication of any FAF whatsoever. Also no activity whatsoever in [figure 7](#) – whereas the A in FAF stands for active region.

The new 16001700 construct therefore serves to note excess 1600 \AA brightenings less obvious than FAFs. The brightness range in these ratio panels is set to 1.5 – 2.5 based on inspection of EB- and FAF-rich data. The lower threshold excludes excess $1600/1700$ brightening in ordinary magnetic concentrations (MC) masquerading as pseudo-EB ([appendix A](#)). The upper threshold does accommodate EBs and FAFs but such large enhancements are not reached here.

A complication in the construction of these ratio panels is that they need correction for the apparent limbward shifts of MC brightenings. This is also detailed in [appendix A](#).

The yellow plus signs mark the locations that I clicked manually in zoom-in *showex* inspection of [figure 1](#) and in parallel of [figures 14–15](#), blinking the latter pair to find the best match, to select each ROI location.

The small yellow arrow to the upper right in the leftmost continuum panel at the bottom shows the local limb direction. Its length corresponds to the projection of a 3600 km tall upright structure (my `heightdiff` value for the 304 \AA chromosphere). Roughly this arrow indicates the minimum position shift one may expect between the surface and EUV samplings.

The axis scales are SDO-size arcsec for both, corresponding to 441.4 km on the Sun. For the SoLO cutout they refer to the center of the full image. For the SDO cutouts the arcseconds are stretched by de-foreshortening but the cutout centers are non-stretched sub-SDO (X, Y) values.

¹³ But not obtaining the actual view from above because the projection and blocking in slanted viewing remain. Remapping cannot repair that the Sun is 3D non-spherical although we zoom her 2D flat and describe her plane-parallel.

Per diagnostic the greyscale of each cutout is set by bytescaling the whole-field sequence, making brightenings comparable between different ROI figures.

My inspections of these assemblies were unusual for me because in all my SDO–STX (usually SST but also DST and IRIS) co-alignments I have always searched for bottom-up cause-effect order. So far my searches concerned happenings in the photosphere or chromosphere that would or did not cause hotter and higher EUV response.

The SoLO campfires are dense and hot features of which the cause is the issue here – but the disturbance causing them may also come from above, as in the blobby coronal rain of [Antolin et al. \(2012\)](#) and flocculent flows of [Vissers and Rouppe van der Voort \(2012\)](#). The assembly rows are ordered top down from $\text{AIA } 193 \text{ \AA}$ to the HMI continuum, but so comparisons should be made in both directions. At least the arrow of time from left to right should be unique.

Let me comment on these ROI figures one-by-one:

ROI-1. This is the arrow-marked campfire in the annotated version of the high-resolution image in the SoLO press release.¹⁴

The SoLO cutout on top shows an upward arc that is not present at the same time in $\text{AIA } 171 \text{ \AA}$ while weakly present in $\text{AIA } 193 \text{ \AA}$ and seen best in $\text{AIA } 304 \text{ \AA}$ where it stays a few minutes.

The four AIA EUVs are all also bright at $\Delta t = -5$ min and then re-brighten during two minutes from $\Delta t = -1$ min, suggesting recurrence. Inspection with *showex* indeed showed larger previous brightening, maximal 7 min before the SoLO moment.

There is a bipolar MC pair at the surface with significant excess brightening in $\text{AIA } 1700 \text{ \AA}$ and also momentary 1600 \AA excess brightening in the 16001700 construct that peaks at $\Delta t = -2$ min and then decays.

The granules in the bottom row are as uninteresting as always. I hoped to see vorticity around the campfire site but don't see this. There may be granular convergence to the yellow cross but this is hard to tell at HMI image quality.

Top-down or bottom-up?

The MC pair at the exact location (account for the projection arrow in the first bottom panel), its brightening in 1700 \AA and its larger-than-usual excess brightening in 1600 \AA suggest bottom-up with the MCs as agent.

However, the 16001700 brightening is weaker than EBs which do not make it to hot AIA wavelengths, and if they did one would not expect the precise co-spatiality of the bright grain in 171 \AA and 193 \AA seen here. FAFs do show effects in these high-temperature diagnostics but as distant expanding arcs ([Vissers et al. 2015](#)). Apparent campfire co-spatiality is also seen in the 193 \AA – detector blink pairs in the limb triples ([figures 35–46](#)).

Top-down supposedly means for such a small disturbance propagating down from the ionized corona that it follows field lines and so naturally ends up in a surface MC since all field lines are rooted in such. The earlier 1600 and 1700 brightenings may then follow from a similar earlier disturbance dropping from above. Indeed, in *showex* they show the 7-min earlier brightening too, reaching maximum at small (about 12 s) delay.¹⁵

¹⁴ I think that (as usual) the selection was not a “typical” (= average) example but rather the nicest.

¹⁵ *Showex* can also plot timelines per pixel. The AIA UV exposures sampled at 24 s cadence are interpolated with all others to the 12-s 171 \AA timings in

The AIA 304 Å row inspired me to add [appendix B](#). The campfire feature is most extended and complex here, and there are larger fuzzy patches around it. In both bottom-up and top-down scenarios one would expect it to show up between the UVs and the hotter EUVs in size and appearance. The simultaneous visibility of the arc in the SoLO image and in 304 Å might then suggest that SoLO includes a cooler line in its 174 Å passband.

However, to me the fuzzy long-lived AIA 304 Å appearance suggests response to irradiation from above followed by temporal non-E visibility extension as described in [appendix B](#).

ROI-2. Not a single flame but a more complex multi-feature campfire in the SoLO cutout at the top. AIA 193 Å mimics it best. Its continuous presence and the presence of mixed-polarity MCs on the surface suggest that this is a bottom-up feature of the type I call brushfire and show in the next section. The agent causing it happened before these sequences.

ROI-3. Weak brightening at the center of a fuzzy diabolo-shaped feature. Both are clearest in the SoLO cutout. Nothing in the 16001700 panel, weak monopolar MCs on the surface. The diffuse surrounding 304 Å brightness again suggests hot irradiation from above.

ROI-4. Rather like a weak version of ROI-1 but without precursor. A nearby MC on the surface surrounded by weak opposite-polarity MCs. Again the feature is most extended and fuzzy in 304 Å.

ROI-5. Similar to ROI-4. Brightest in AIA 131 Å at just the SoLO moment.

ROI-6. Similar again but embedded in a longer rather persistent feature.

ROI-7. Local brightening in the SoLO cutout but not standing out in any SDO panel. Perhaps foreshortening blocking by the fuzzy surroundings best seen in the 304 Å panel.

ROI-8. Present in the SDO EUV panels, also earlier, then fading. Again 304 Å shows the most extended surroundings. The 16001700 panel has an excess feature but dislocated.

ROI-9. Already present at the start, with some mixed-polarity field on the surface. Perhaps a small brushfire.

ROI-10. Weak but also persistent from the start, with some mixed-polarity MCs on the surface.

ROI-11. Truly a SoLO campfire because there is nothing in any AIA diagnostic including the fire detector in [figure 69](#). AIA 171 Å shows weak streaking in the same direction, that's all. Nothing at its location in the HMI magnetogram. The bright SoLO streak may be just that, higher up and may be blocked by foreground opacity in the slanted AIA viewing through the gas above the large brushfire of ROI-D.

ROI-12. Local brightening in a small brushfire.

7. SoLO–SDO brushfire cutouts

In this section I add similar cutout figures for some of the larger bright patches in [figure 1](#). I call these “brushfire” after language correction by Ron Moore ([footnote 6](#)). They likely all are regular “coronal bright points” but I keep to my phenomenological nickname in this purely observational inventory.

my pipeline. All samplings along columns are synchronous, as are the triples in [figures 17–46](#).

I selected five called ROI-A – ROI-E. Their locations and the corresponding ROI cutouts in the SoLO 174 Å image are shown in [Figure 60](#). These cutouts measure 36×36 arcsec².

[Figures 61–65](#) again show a selection of SDO diagnostics. The column timings are now respectively 9, 6, and 3 min before the best-match time in the last column.

All five EUV-bright patches remain more or less the same during these nine minutes, so that discussing their origin is literally beyond this study: for each it took place or started before my downloaded SDO sequences.

However, all five sit above locations with somewhat enhanced mixed-polarity network. [Figures 66–69](#) show the HMI magnetogram of [figure 7](#) and various EUV diagnostics with all ROI boxes superimposed. Blinking shows that also all other bright EUV patches of brushfire size sit above similar mixed-polarity network concentrations, whereas campfires, as SoLO prototype number 1, can be at quieter monopolar locations.

It therefore seems likely that the brushfires are all bottom-up cases resulting from magnetodynamic opposite-polarity interactions on the surface. The same is suggested by the high degree of correspondence between larger fires and somewhat denser mixed-polarity MC assemblies in the “other” SDO scenes in [figures 17–46](#).

8. Discussion

Campfire nature

By definition the SoLO campfires are “EUV bursts” or “SoLO bursts”.

Initially I did not check the extensive literature on coronal (X-ray) bright points¹⁶ as to whether these little SoLO critters have earlier been noted, described, analyzed in this bright-point context. This might well be the case since I found them also in the SDO images and archive – but perhaps they were just too small, scarce and inconsequential to excite interest.

Classical coronal bright points, recently reviewed by [Madjarska \(2019\)](#), extend 10–60 arcsec, are bundled short loops bright at EUV and soft-X-ray wavelengths, and typically live multiple to many hours. They are the larger fires here that I phenomenologically called brushfires.

However, after my initial arXiv post ([2009.00376](#)) Ron Moore pointed me to [Falconer et al. \(1998\)](#). This beautiful study compared quiet-Sun coronal activity with underlying network much as displayed here in triple [figures 17–46](#). Their example [Fig. 1 \(pdf 2\)](#) from SOHO/EIT is similar to [figure 1](#) and the ten AIA 193 Å triple members here. Their KPNO magnetograms ([their Fig. 2 \(pdf 4\)](#)) appear less sharp but of higher sensitivity than the HMI magnetograms here. They detected hundreds coronal bright points in their six combined data sets. Most were supergranular-cell size and therefore classical ones, but there were also smaller ones, even down to the 2.6 arcsec EIT pixel size¹⁷. These one-pixel EIT brightenings were likely campfires – long avant la lettre.

¹⁶ SoLO campfires are surely “bright points” at lower resolution. Solar physicists have a bad habit of calling unresolved features “points” – in [Rutten and Uitenbroek \(1991\)](#) we went from Ca II K_{2V} and H_{2V} internetwork “bright point” to “grain”; for “magnetic bright point” I use “magnetic concentration”. At least umbral dots are not points.

¹⁷ SOHO arcsec, not as close as SoLO but a teeny bit closer than SDO.

Falconer et al. (1998) concluded that most if not all quiet-Sun coronal heating is driven by bipolar network interactions. The canonical view of coronal bright points (or Skylab X-ray bright points) is indeed that these bright small-scale loop systems connect network MCs with opposite polarities (Madjarska 2019). Blinking the triples in figures 17–46 vividly confirms this.

The exception to bipolar MC footpoint driving may be campfires as in ROI-3 in figure 50 and ROI-6 in figure 53. They show only minor underlying MCs in their HMI magnetogram cutouts – but still some and the low HMI sensitivity sets a severe detection limit. If strong bipolar MC canceling occurred at campfire sites one should observe EBs; their absence already requires weaker interactions only whereas even EB cancelations are already difficult to find at HMI quality (see comparisons in figure 4 (pdf 6) of Rutten et al. 2013).

So what are campfires?

Their apparent co-spatiality in the 193 Å – detector limb triples (figures 35–46) suggests chromospheric location.

They are not EBs or FAFs: not in active regions and no excess 1600 Å brightenings.

They are not quiet-Sun QSEBs: no excess 1600 Å brightenings, and QSEBs do not become EUV-bright.

They are not spicule-II tips at the end of RREs or RBEs: far too scarce and not emanating from and around network.

What else as bottom-up disturbance candidate?

Vortices come to mind (“swirls”, “tornadoes”, “cyclones”). The original granulation-flow vortex of Brandt et al. (1988) extended 7 arcsec; later detections went smaller (e.g., Attie et al. 2009, Bonet et al. 2010, Vargas Domínguez et al. 2011, Wedemeyer-Böhm et al. 2012, Liu et al. 2019b, Liu et al. 2019a). Mesogranular-scale vortices occur at about ten times higher density than campfires while Figure 3 (pdf 5) of Tziotziou et al. (2018) does not show bright EUV response to a long-lived one. Maybe campfires mark rare unusually large multi-granule vortices.

Yet larger prominence tornadoes detected in AIA 171 Å (e.g., Wedemeyer et al. 2013, but see Panasenco et al. 2014) aren’t campfire candidates since there are too few filaments in the SDO fields here.

Granular-size swirls occur at least a hundred times more than campfires. Obviously no campfire agent, but since spicules-II show multiple wave signatures including torsion (De Pontieu et al. 2012, Rutten 2013) while emanating from network (mono- or bipolar), it may well be that granular swirls affecting embedded MCs contribute to or cause the quiet chromosphere.

I showex-inspected the HMI granulation around the campfires searching for apparent vorticity in time-sliding, but the HMI-continuum granulation seems too low in quality for such visual detection or for reliable small-scale flow mapping and vorticity charting.

What rests are top-down candidates.

Particle beam impacts are a familiar flare phenomenon but are also suggested to occur in small-scale nanoflare context from higher-up filamentary reconnection near the apex of thin loops. Such reconnection may generate beams of energetic particles that travel along field lines down to their footpoints and heat the underlying chromosphere there (e.g., Bakke et al. 2018, Frogner et al. 2020). This seems a good way to explain small-scale and

deeply-located cospatial 304 Å and 131 Å brightening up to cyan intensities in the fire detector images as coming from above, with particle beams penetrating deeper than conduction in partially neutral chromospheric gas (Fig. 13 (pdf 14) of Frogner et al. 2020).

In this scheme cyan detector footpoints of short-loop brushfires in 193 Å mark higher-up intermittent reconnection imposed by bipolar network dynamics affecting their feet, with recurrent brushfire longevity imposed by continuous network replenishment as described by Schrijver et al. (1997). The field-topology reconnection cause for brushfires is then bottom-up into the corona while concurrent local chromospheric foot heating results top-down from there.

The small momentary non-arch campfires may then mark yet smaller and more incidental higher-up reconnection events with a resulting particle beam lighting up the chromosphere underneath into brightness in all AIA EUVs.

A very different heating-from-above option: axion quark nuggets are claimed to impact the Sun and so not only explain SoLO campfires but also all solar EUV emission, solar impulsive radio events, coronal heating and hence the solar wind, and then also all dark matter (search “axion campfires” on arXiv, not cited here because I won’t).

Instead I wondered about more mundane Sun-impacting meteors and consulted AIA-comet-impact expert Karel Schrijver. He suggested instead CME left-over return into the Sun and sent me a dramatic AIA 193 Å movie taken 2012-12-14 as an example. It shows very blobby (“flocculent”) downpour back onto the lower atmosphere. Karel suggested that SoLO campfires may represent small versions of such blobby return splashes, and that perhaps AIA difference movies might indicate such even at their coarse resolution.

In the ROI cutouts the brushfires are most probably bottom-up cases originating in bipolar field interactions on the surface. Also the campfires that appear as small brushfires (ROI-2, 9, 10, 12 – unattended campfires?). But for the prototype ROI-1 campfire in figure 48 and similar others (ROI 3 – 8) a small post-CME splash-down blob may be a viable mechanism.

If so, the ROI-1 blob splashed down into a surface MC. Blinking figure 67 against figure 66 shows that there is not a single ROI, campfire or brushfire, without MCs underneath – while there is as much non-magnetic grey internetwork area to splash down in for non-discriminating splashes. However, impacting post-CME blobs likely remain charged and follow field lines to roots on the surface, just as post-reconnection particle beams do. The smallest cyan-colored fires in the fire detector scenes in triple figures 17–46 are indeed all located in grey network-chromosphere patches.

Quiet-Sun heating

The campfires obviously display heated atmosphere, but the AIA images in figures 12–15 show no obvious effect on their surroundings. In cutout figures 48–59 diffuse AIA 304 Å brightness around them suggests wider spreading, but I attribute that to EUV irradiation from above (appendix B).

The larger brushfires in the AIA 193 Å images seem to initiate larger-scale loops and diffuse coronal connectivity around them, but the tiny campfires do not. As smallest instance of the coronal

bright point phenomenon they also seem the least important in coronal heating.

A non-expected result of this study is the remarkable efficacy of the fire detector 304×131 product in separating quiet-Sun chromospheric and coronal heating. The detector images show very distinct appearances between these, suggesting very different mechanisms.

Heated quiet-Sun chromosphere appears in the detector images as grey patches everywhere. These have the same surface pattern as reversed GONG-H α brightness patches because both spread around quiet network. They occupy the same space with the same gas but in different phases of small-scale dynamic heating and cooling which occurs ubiquitously around quiet network, whether monopolar or bipolar. [Appendix B](#) gives background and detail.

Heated quiet-Sun corona appears in the AIA 193 Å images as coronal bright points / brushfires and in diffuse wider-connectivity patterns around them. The fire detector images pinpoint their chromospheric feet as cyan pixels, co-spatially heated in AIA 304 Å and 131 Å but not remarkable in H α ([Appendix B](#)). In quiet-Sun areas brushfires result from minor bipolar MC interactions and do not occur at monopolar network (“minor” because there are no EBs or FAFs in the UV sequences; such fierce low-altitude reconnection occurs only in active regions).

Thus, the fire detector images suggest that quiet-Sun heating differs intrinsically between chromospheric and coronal heating. My initial question whether cause-effect relations are bottom-up or top-down has both as answer for both in the scenarios proposed in [Appendix B](#). In brief: in quiet chromosphere spicule-II heating and ionization brighten 304 and 131 Å upward while subsequent downward cooling and recombination of the same gas cause the fibrillar H α chromosphere. In quiet corona bipolar MC footpoint dynamics impose high-up small-scale filamentary reconnection while resulting downward particle beams cause 304 and 131 Å feet brightenings in the chromosphere.

Whether the vaguer diffuse coronal connection patterns in the AIA 171 and 193 Å images were made exclusively by previous brushfires or by additional other agents cannot be addressed with the short sequences I downloaded for [figures 17–46](#). However, the continued brushfire presence and activity in my 12-hour SDO sequences of the SoLO field around the SoLO moment suggest continuous bipolar MC renewal through newly arriving network replenishment ([Schrijver et al. 1997](#)) and indeed long-term production of the observed larger-scale connectivity.

Campfire prospects

IRIS PI Bart De Pontieu and the SST’s Peter Sütterlin informed me that on May 30 there was no coordinated co-targeting with SoLO.

I hope there will be in future, but the [SoLO orbit movie](#) suggests that in the upcoming SoLO perihelia the mission will be between 70 and 110 degrees in advance or behind the Earth in ecliptic projection.¹⁸ This is promising for STEREO-type dual-sightline studies, but complicates multi-diagnostic same-scene co-targeting because co-pointing Earth-based and near-Earth telescopes will suffer severe foreshortening offset from the

¹⁸ Because SoLO will store its 10-day campaign data taken during its perihelia in spring and autumn far from Earth awaiting delivery during its subsequent mid-winter aphelia when we also get thereabouts for closer download, hence with Earth a quarter orbit off during the taking.

SoLO target scenes, worse than in this study (if not farside from here).

The best time for down-the-throat conjunction co-targeting seems around 2022-03-15 when SoLO first crosses Mercury’s orbit with Earth only about 10 degrees behind in solar-center direction.¹⁹ In June 2027 SoLO in its perihelion and Earth will again be close in ecliptic direction, but then SoLO will be intentionally kicked poleward by Venus for a better view of polar areas sampled here in [figures 35–46](#).

9. Conclusion

Most coronal fires in this report seem controlled bottom-up by MC interactions of quiet mixed-polarity network on the surface, as suggested for X-ray/coronal bright points since Skylab (e.g., [Krieger et al. 1971](#)). They seem to furnish most quiet-Sun coronal heating.

Coronal fire heating is very distinct from ubiquitous chromospheric heating around all network in the fire detector images that separate these classes remarkably well by fire feet marking.

Whether coronal fires mark MC reconnection that may be diagnosed from cancelation, fly-by reconnection that may be diagnosed from MC trajectories, reconnective twisting that may be diagnosed from swirling, reconnective or ion-neutral slingshotting that may be diagnosed from simulation, or Alfvénic wave heating that may be diagnosed from propagation is beyond this study.²⁰

Campfires represent the smallest, scarcest, briefest, least important specimens of the coronal bright point phenomenon. The one-pixel EIT Fe XII 195 Å coronal bright points of [Falconer et al. \(1998\)](#) were a decades-earlier campfire detection. SDO shows them daily in multitudes for a decade already. Blinking the triples in [figures 17–46](#) suggests that they reside at chromospheric heights and do not contribute noticeable coronal heating.

Some smallest campfires, including some original SoLO campfires, may represent exceptions to bipolar footpoint interaction and perhaps mark larger-scale surface vortices or impacting field-guided CME return blobs.

I suggest that coronal brushfire heating corresponds to sets 1 and 2 in [Fig. 12 \(pdf 13\)](#) of [Frogner et al. \(2020\)](#) with particle-beam foot heating giving the fire pinpoint functionality of the chromospheric 304×131 detector product.

For the campfires I suggest that most represent small localized chromosphere heating as in set 3 of this figure. It comes electrically from above, is quickly radiated away, and does not affect the H α chromosphere – making “St. Elmo’s fires” a better nickname for these harmless little electric flames. They may be diagnosed by charting IRIS Si IV Dopplershifts at AIA campfires ([Testa et al. 2014](#), [Polito et al. 2018](#)).

The obvious recommendation from this study is to not await properly validated SoLO images or future SoLO campfire observations but to study them in the SDO database using fire detection as in [figure 69](#) to find them.

¹⁹ I would love co-pointed SoLO EUV/HRI Ly α and HeII 304 Å with SST/CHROMIS H β , SST/CRISP H α and IRIS in view of [appendix B](#), but this is early in the year for best seeing on La Palma. Maybe DKIST by then.

²⁰ Or all contribute adhering to the “Principle of Solar Communicativity” (pdf9) formulated at the only solar IAU symposium ever in the USSR ([Rutten 1990](#)).

If my institute would offer access to studentships and students²¹ I would propose as projects:

1. obtain longer SDO sequences than here and use ROI cutout timeline analysis to study fire recurrence and doubling where multiple feet heating occurs;
2. apply the SDO fire detector of [figure 69](#) to the entire SDO database to assemble campfire statistics as function of the cycle, latitude, open/closed field geometry, etcetera;
3. do the same for more interesting brushfires in relation to larger-scale coronal connectivity patterns. Also produce latitude–time basal coronal heating diagrams in the style of David Hathaway’s beautiful [magnetic butterfly diagram](#);
4. try to find campfires that follow on CMEs with subsequent flocculent rain, first for trial demonstration and when successful with machine learning for the entire SDO database;
5. search for granular and/or MC vortices at fire sites. For SoLO use simultaneous SoLO/PHI granulation imaging. For SDO use simultaneous Hinode/SOT or groundbased granulation imaging. Expand to chromospheric vortices where chromospheric diagnostics are available. Expand if possible to the SDO database when successful;
6. use Bifrost or MURaM simulations to replicate and demonstrate the apparent brightening differences and limb shifts of MCs between different ultraviolet wavelengths, including the AIA, TRACE and IRIS/SLI ones;
7. use SST/CHROMIS observations in the extended Ca II H & K wings to study MC stratifications following [Sheminova et al. \(2005\)](#), extend these to larger height with IRIS Mg II h & k scans, do so for quiet network and brushfire–feet mixed-polarity network, also cover center-to-limb sampling, and compare with Bifrost or MURaM mixed-network simulations with H & K and h & k wing synthesis using RH 1.5D ([Pereira and Uitenbroek 2015](#));
8. develop a FAFDETECT algorithm and search the SDO database for slow wind sources as in [Brooks et al. \(2015\)](#);
9. use machine learning to search the SDO database for retarded correlation of AIA 304 Å brightenings after AIA 1600 Å brightenings, and also of AIA 304 Å brightenings after flocculent CME return flows in the hotter AIA’s. Best done with early SDO data when AIA 304 Å had higher signal-to-noise;
10. use automation on the SDO and GONG H α databases to select the best H α images, de-stretch and co-align these precisely with AIA 304 Å and quantify pattern equality including relative time delay. Better would be to find sharper joint data sets for these two lines and use those. Yet better would be to add ALMA imaging.

Appendix A: AIA 1600 and 1700 Å comparison

My initial impression from watching the press conference was that SoLO campfires might be FAFs. I therefore elaborate on these here. The way to find them is by comparing AIA 1600 Å images to 1700 Å images which is also a good way to find EBs beyond the blue wing of H α . Comparing these UV images brings intricacies also detailed here.

²¹ If a student of this report desires to use material or techniques used here I likely will cooperate.

I start this explanation with EBs because ultraviolet EB and FAF detections are coupled, although it was evident already during the press conference that campfires are not EBs or QSEBs because neither type of low-atmosphere reconnection reaches EUV visibility.

EBs and FAFs

EBs²² were discovered and defined by [Ellerman \(1917\)](#) as sudden small brightenings in active regions in the outer wings of the Balmer lines. By now it is well-established that EBs mark strong-field reconnection in the low photosphere that does not break through the overlying chromospheric canopy of H α fibrils. “Strong field” means kilogauss “fluxtube” magnetic concentrations (MC) in the [Spruit \(1977\)](#) sense, but they don’t have to cancel completely, only partially, which means that in coarse SDO/HMI magnetograms one does not observe bipolar feature pairs vanishing against each other at EB sites. At higher resolution, as from the SST in the third row of [figure 4 \(pdf 6\)](#) of [Rutten et al. \(2013\)](#) as compared to the fourth HMI row there, one does see partial vanishing. I believe that EB cancelations have not yet been studied at the so-far highest resolution and magnetic sensitivity (both needed) of Hinode’s SOT/SP, perhaps because Hinode’s H α imaging first suffered bubbles and then died.

EBs are observed per Ellerman definition in the outer wings of the Balmer lines and also in Ca II H & K, but not in the Na I D and Mg I b lines ([Ellerman 1917](#), [Rutten et al. 2015](#), [Rutten 2016](#)).

A decisive characteristic is bright-flame appearance when observed towards the limb ([Watanabe et al. 2011](#)).

They also stand out in AIA 1700 and yet more in 1600 Å images through metal ionization leaving only the Balmer continuum and Rayleigh scattering as opacity agents ([Rutten 2016](#)).

The best way to spot potential magnetic cancelations at EB sites with SDO is not searching for MC cancelation in HMI magnetograms but detecting fast convergence of magnetic bright points in AIA 1700 Å that mark opposite-polarity MCs.

[Roupe van der Voort et al. \(2016\)](#) reported QSEBs = “quiet-Sun Ellerman-like brightenings”. These are similar partial MC reconnections but in quiet network away from active regions. [Danilovic \(2017\)](#) simulated them with MURaM; [Joshi et al. \(2020\)](#) found more and more detail with H β images from SST/CHROMIS, twice sharper than SST/CRISP H α (like SoLO over SDO).

Neither EBs nor QSEBs are of interest here because their reconnection heating doesn’t reach EUV-line temperatures. Their role here is their AIA UV detectability.

FAFs²³ are also easily identified through enhanced brightness in the ultraviolet continua sampled by SDO. In contrast to EBs

²² EB naming: [Ellerman \(1917\)](#) called them “hydrogen bombs”. “Ellerman bombs” came from [McMath et al. \(1960\)](#) but I now prefer “bursts” since the border-police-challenging b-word in my laptop cost me that laptop.

²³ FAF naming: problematic. In [Rutten et al. \(2013\)](#) we noted them as “small flaring arch filaments and microflares”, I think following a report by Brigitte Schmieder – but I don’t remember which and she has too many non-open-access for easy search. [Pariat et al. \(2009\)](#) noted them in 1600 Å images from TRACE, called them “transient loops”, and reported them as a new phenomenon – but probably Ca II K “microflares” (e.g., [Shimizu et al. 2002](#)) described similar outbursts. We used FAF = “flaring arch filament” in [Vissers et al. \(2015\)](#) but in [Rutten \(2016\)](#) I proposed “flaring active-region fibril” to avoid confusion with the larger and stabler structures making up “arch filament systems” in emerging and flaring active regions.

they are less round, move fast along filamentary tracks, and appear more enhanced in 1600 Å, presumably from C IV contributions. They start as similar photospheric partial MC reconnection events, but their reconnection proceeds upwards to above the $H\alpha$ canopy as emulated in numerical MHD simulations by [Hansteen et al. \(2017\)](#). They may leave signatures in the hotter AIA EUV diagnostics but these appear as rapidly expanding arcs (perhaps shells) that are hard to detect ([Vissers et al. 2015](#)).

EBFAF movies

I started on EBFAF detection while reviewing the EB literature for [Rutten et al. \(2013\)](#). I found that many older but also recent publications erroneously addressed ordinary MCs as EBs although [Ellerman \(1917\)](#) already warned against this – we then called these “pseudo-EBs”.

I then wrote `sdo_makeeblocmovie.pro` which produces EBFAF movies comparing AIA 1600 to 1700 Å. I experimented with subtraction, division and multiplication of the two after normalizing each to its mean, and settled on multiplication. In the 1600×1700 panels of these movies EBs stand out dramatically by being very bright while roundish and stationary during a few minutes; FAFs are as bright or yet brighter but have elongated shape and move very fast along filamentary paths.

Triggered by EB-manuscript referee requests I then got some years into the habit of checking any new EB publication by producing and inspecting corresponding SDO EBFAF movies, including [Nelson et al. \(2013a\)](#), [Vissers et al. \(2013\)](#), [Bello González et al. \(2013\)](#), [Yang et al. \(2013\)](#), [Nelson et al. \(2013b\)](#), [Hong et al. \(2014\)](#), [Peter et al. \(2014\)](#), [Nelson et al. \(2015\)](#), [Vissers et al. \(2015\)](#), [Kim et al. \(2015\)](#), [Rezaei and Beck \(2015\)](#) and more that I don’t remember.²⁴ I showed these at various meetings.

EBDETECT

[Vissers et al. \(2019\)](#) perfected EB finding in AIA UV images combining ten SST–SDO data sets for evaluating different options. The resulting `EBDETECT` program uses AIA 1700 Å to avoid FAFs and finds most of the stronger $H\alpha$ EBs by setting a severe brightness threshold (over 5σ above mean) as well as lifetime and size requirements.

With this recipe the entire SDO database is accessible to study the occurrence of strong EBs, whereas all EB studies before were limited to small fields sampled briefly in $H\alpha$ with groundbased telescopes.

FAFDETECT

[Vissers et al. \(2019\)](#) did not develop an analogous FAFDETECT program, but it would be a similar effort and similarly contain a severe brightness threshold but then require elongated shape and fast motion along filament-shaped tracks.

I suspect it would be worthwhile to let also such a detector loose on the SDO database. For example, when a [slow-wind source map \(pdf 26\)](#) was published by [Brooks et al. \(2015\)](#) I made corresponding preceding EBFAF movies and noted that the wind-

producing active regions were also rich in FAFs, i.e., in having canopy-piercing reconnection events.

AIA 1600/1700 with limbshift correction

Inspection of [figures 9](#) and [8](#) (or rather the corresponding cube files using `showex`) showed immediately that running `sdo_makeeblocmovie` or `EBDETECT` makes no sense for this quiet area.

Nevertheless, I wanted some indication of excess AIA 1600 Å brightening over 1700 Å brightening while lower than for EB or FAF localizing. Renewed experimentation brought me to division instead of multiplication.

A complication arose for such weaker excess detection: the apparent limbward shifts of MCs in AIA 1600 versus 1700 Å. It is immediately obvious per `showex` when zooming in to near-limb areas, showing displacements up to half an AIA 0.6 arcsec pixel.

[Figure 70](#) displays them as shift vector chart. Such figures are an optional byproduct of my SDO cross-alignment pipeline for many years already, but I have not published any.

[Figure 71](#), also a regular product, shows that these apparent shifts increase linearly limbward and that radial components dominate them.

In [figure 72](#) each subfield “tile” (similar to those in which the pipeline splits the disk-center JSOC cutouts for SDO cross-alignments) has been shifted back with radial counter-shift increasing to 220 km at the limb before cross-correlation. The vectors in this residual shift chart are much smaller but show large-scale patterns. I then made such residue charts for the first minute of every month of the 10 full SDO years so far and found to my surprise that this pattern is roughly the same on all. I don’t know whether it comes from errors in my programs or from fixed small-scale imaging difference between the two bands, but the amplitudes are only of order 0.1 px (~ 40 km) and negligible in my cross-alignment averaging over many tiles.

Since last year apparent limbshift corrections as these are applied in my SDO cross-alignment pipeline; they improved it. In particular, they enabled using AIA 304 Å versus HMI magnetograms as “anchor” pair to couple the EUV channels directly to HMI, bypassing the UV channels I used before in an intermediate step. This gives better `driftscenter` results because magnetograms sample a thinner atmospheric layer and so suffer less from such apparent shifts and from blocking by foreshortening. The result for the present SDO download is shown at left in [figure 75](#).

MCs in AIA 1600 and 1700 Å

I conclude this UV appendix by discussing the reason for the apparent 1600 versus 1700 Å brightening and limbward shifts of MCs.

Plane-parallel colleagues attribute both to larger opacity at 1600 Å due to increased Si I photoionization, and possibly larger C IV contributions. I doubt the latter because the tile chart in [figure 71](#) is regular and does not reflect EUV brightness patterns. Only near and at the limb do I note sight-line integrated C IV contributions.

Higher 1600 Å formation is correct for idealized gas in the VALIIC plane-parallel solar analogon star of [Vernazza et al. \(1981\)](#) and indeed evidenced in [these panels of their informa-](#)

²⁴ The worst identified over 3000 EBs “radiating enough excess energy to heat the corona” – but they were all ordinary MCs, pseudo-EBs, that do not obtain excess brightness from heating and anyhow radiate that away. The best was where my SDO inspections reversed the conclusion of the manuscript.

tive Fig. 36 (pdf 39). A plane-parallel plage model with outward increasing facular temperature excess then also explains facular 1600 over 1700 Å brightening.

Such plane-parallel construct was the basis for often-followed facular SATIRE irradiance parametrization in Unruh et al. (1999) which uses the FALP model of Fontenla et al. (1993) although discarding its chromospheric temperature rise to avoid strong-line core reversals from assuming LTE line formation (the classical trick of Holweger (1967) underlying the formerly popular but equally unrealistic model of Holweger and Müller 1974).

However, in non-plane-parallel solar reality this explanation fails entirely. MC brightening and enhanced MC brightening are *not* due to extra heating with upward increasing excess but to non-plane structure viewing. MCs appear bright because they are holes in the surface sampling higher temperatures underneath, brighter when seen deeper. The observed 1600 versus 1700 Å brightness enhancements and limbward offsets are due to *smaller* opacity at 1600 Å, resulting in more apparent MC transparency. It gives deeper hole viewing from above and deeper penetration beyond holes in slanted viewing. Figure 73 and its caption review how and why. Old stuff but ignored in irradiance modeling.

For continuum bright points, G-band bright points and faculae non-heated multi-D hole viewing has been properly reproduced with numerical simulations by Keller et al. (2004), Carlsson et al. (2004), Steiner (2005) and Vitas et al. (2009). The dark limbward MC foot was emphasized by Steiner (2005) and is clearly observed near the limb in AIA 1600–1700 Å zoom-in showex blinking. Together with the growth of the bright stalk sampling the granule behind, these combined morphology changes explain the apparent limbward shifts in figure 70.

Such MURaM and Bifrost simulations might easily be extended to 1600 Å versus 1700 Å formation comparison and furnish a sounder network/plage recipe for irradiance modeling. Relatively easy because non-E and ion-neutral separation play no role so deep in the atmosphere; the hardest part is accounting for the non-LTE ultraviolet line haze (Rutten 2019).

Appendix B: AIA 304 Å and GONG H α comparison

Chromosphere in H α and He II 304 Å

Figures 11 and 12²⁵ show coarsely similar patterns in greyscale-reversed H α and He II 304 Å. Figure 74 demonstrates this similarity statistically.

One would expect that observing some atmospheric domain or structure in the one line would exclude observing the same in the other line, since HI should be fully ionized where He I is ionized at its twice larger ionization threshold.

Indeed in plane-parallel standard models H α samples the middle chromosphere²⁶, whereas He II 304 Å samples the much hotter

²⁵ I co-aligned these two images with findalignimages.pro which is my engine for SDO–STX co-alignments. It uses iterative best-fit determination of relative scales, shifts and rotation with Tom Metcalf’s auto_align_images.pro in SSW. I applied the results per reformimage.pro. In this case the trick was to blur both images considerably. When blinking this pair the scenes appear to jump, but detailed showex inspection confirms close alignment.

²⁶ The so-called “chromosphere” with temperatures around 7000 K in standard models as VALIIC of Vernazza et al. (1981), FALC of Fontenla et al. (1993) and ALC7 of Avrett and Loeser (2008) is wrongly named. There it is primarily defined by fitting apparent ultraviolet brightness temperature maxima reached in acoustic shocks (Carlsson & Stein 1994, 1995), emphasized because linearly attributing mean brightness intensity to mean temperature doesn’t hold in the Wien

“transition region” in these models. Observed pattern similarities would then imply that these discordant (mutually exclusive) regimes vary jointly in mapping local opacity/emissivity variations that similarly affect the chromosphere and overlying transition region.

I think that this is seriously misleading oversimplification. To me the reversed H α and 304 Å scenes look too similar.²⁷ I pose that both lines show the “chromosphere” defined by Lockyer (1868) as what one sees in Balmer lines and He I D₃.

I suggest that assuming statistical equilibrium (SE) is wrong for H α and possibly wrong for He II 304 Å in situations where previously heated gas cools and recombines – and I suggest that this occurs always and everywhere in chromospheric canopies covering the clapotisphere. The latter is already shockingly dynamic as proven by Carlsson and Stein (1997) and its low-altitude post-shock-cooling internetwork gas gets very far out of SE for hydrogen (Leenaarts et al. 2007).

Thus, I see the chromosphere around quiet network, i.e., the H α fibril canopies that figure so prominently in any H α filtergram, as a domain that is continually pervaded and renewed by “propagating heating events” (PHE), far from static or statistical equilibria; a domain in which most dark H α features result from opacity boosting in dynamic cooling events with hot onsets (Rutten 2016, 2017b, 2017a; Rutten and Rouppe van der Voort 2017, Rutten et al. 2019).

In this view the similarity and co-correlation of the quiet H α chromosphere and the quiet He II 304 Å chromosphere result because both represent dynamism that is patterned by underlying magnetic network: dynamic heating for 304 Å, subsequent dynamic cooling for H α . They do not show the same chromosphere instantaneously but they do obey the same underlying network patterning in showing gas in different stages of intermittent ionization and recombination.

A corollary of dynamic non-equilibrium H α opacity boosting is that H α fibril canopies should also be opaque at the ALMA wavelengths and hide the clapotisphere from its solar view, in conflict with SE-based numerical predictions. ALMA is often advertised as LTE thermometer, hence obey SE to the extreme, but its intensities represent temperature directly only for optically thick features whereas the ALMA opacities defining these thicknesses, hence feature visibility, get very far from SE in cooling gas. Non-equilibrium cool-after-hot retardance affects the whole top of the hydrogen term diagram, similarly boosting the H α and HI free-free opacities by orders of magnitude. Since clapotisphere shocks (Ca II H_{2V} and K_{2V} internetwork grains) are nowhere visible in canopy-dominated H α -core images they cannot be seen with ALMA either (Rutten 2017b),

This prediction is getting confirmed (Molnar et al. 2019, da Silva Santos et al. 2020, Chintzoglou et al. 2021) and simulated (Martínez-Sykora et al. 2020a), implying indirect confirmation of the dynamic non-equilibrium nature of the chromosphere.

part of the spectrum. These clapotispheric shocks sit under the H α fibril canopies that are the on-disk Balmer-line counterpart to Lockyer’s (1868) off-limb line-colored ring which is made magnetodynamically, not hydrodynamically.

²⁷ This struck me first when watching the marvelous AIA video wall at LMSAL with Marc DeRosa in 2011. All other EUVs showed the corona in various disguises but this diagnostic showed chromospheric patterns roughly as H α does with its extended fibril canopies, unique in chromosphere rendering. That splendid view inspired my work since. I concentrated on H α and some Ly α , but it is time for He I 10830, He I D₃, He II 304 Å. While missing He I 584 Å I welcome SoI’s EUV/HRI Ly α capability.

Dark in $H\alpha$ versus bright in He II 304 Å

The $H\alpha$ greyscale reversal that helps to obtain pattern match with He II 304 Å between [figures 11](#) and [12](#) (quantified in [figure 74](#)) also supports my view. With static and statistic equilibria it is hard to explain that a dark feature in the one should match a bright feature in the other as these figures show.

$H\alpha$ is a heavily scattering line in which fibrils that are very optically thick become very dark from the [Avrett \(1965\)](#) $\sqrt{\epsilon}$ scattering law, lowering their line source function towards the feature surface (see [Section 4.3 \(pdf 112\)](#) of [Rutten 2003](#) or the summary in [Section 3 \(pdf 7\)](#) of [Rutten 2019](#)). Cool-after-hot non-E opacity enhancement darkens these $H\alpha$ features considerably. Such enhancements reached even factors 10^{12} for $H\alpha$ in cool-down after internetwork shocks in the simulation of [Leenaarts et al. \(2007\)](#), shown in the last panel of [this movie of their Fig. 1](#).

On the contrary, most hot coronal features are optically thin or at least effectively thin in the AIA EUV diagnostics; the greyish He II 304 Å patches in [figure 12](#) likely also. Then one doesn't talk source function but just emissivity. In lines the first is set by the ratio of upper and lower level populations, the second by the upper-level population alone ([equations 2.71 and 2.69 \(pdf 44\)](#) of [Rutten 2003](#)). Avrett $\sqrt{\epsilon}$ darkening requires feature thickness beyond thermalization lengths. $H\alpha$ fibrils are thick enough that the population ratio is set by $\sqrt{\epsilon}$ darkening, more for larger opacity = larger lower-level population. For He II 304 Å larger upper-level population gives larger brightness to thin or thinnish features.²⁸

Thus, observing the same gas bright in He II 304 Å and dark in $H\alpha$ requires substantial emissivity in the first, large opacity in the second. In SE these are mutually exclusive for given temperature, as in standard models, but in cooling-after-hot gas they may coexist sequentially with non-E retardation.

Another ALMA corollary is the prediction that ALMA images of the quiet chromosphere show patterns coarsely similar to reversed $H\alpha$ and AIA 304 Å images. Direct ALMA – 304 Å cross-correlation will be hampered by the small ALMA field size; it is likely better to use GONG $H\alpha$ as intermediary since that can first be co-aligned with AIA 304 Å using large center cutouts as in my [gong_sdo.pro](#).

Non-E fibril canopies in $H\alpha$ and He II 304 Å

For $H\alpha$ [Rutten et al. \(2019\)](#) showed that many dark fibrils constituting dense canopies around network are made by spicules-II appearing as $H\alpha$ -wing RBEs and RREs on the disk. The latter are not detected in GONG wide-band images, but their subsequent fibrillar products show up as unresolved grey patches in reversed [figure 11](#).

The dark fibrils follow a few minutes after the spicule-II heating jets, as cooling backflow gas maintaining the large $H\alpha$ opacity gotten in the hot onset through non-E retardation during subsequent minutes. Their opacities then decline gradually but their opacity excess over actual-temperature SE estimation (non-

²⁸ Filaments are also dark in $H\alpha$ from scattering photospheric radiation (often with underneath brightening by backscattering as observed by [Kostik and Orlova 1975](#)) and may well be non-E-enhanced opaque and dark since they appear ridden through by frequent disturbances. When filaments are also observed darkly in He II 304 Å this is more likely due to frequency-redistributing bound-free scattering of chromospheric radiation in the H I Lyman and He I continua ([Figure 10 \(pdf 12\)](#) of [Rutten 1999](#)) in which every interaction darkens the intensity, whereas resonance scattering needs many interactions for $\sqrt{\epsilon}$ darkening.

LTE population departure coefficient b_2 of $H\alpha$'s lower level) increases rapidly. Even if these fibrils cool enough to show strong CO lines they can still be prominently opaque and dark in $H\alpha$.

The contrail of [Rutten and Rouppe van der Voort \(2017\)](#) was a prototype of dark-fibril production. Its subsequent retraction was evident from the later $H\alpha$ Doppler profiles in [their Figure 4 \(pdf 5\)](#). In the statistical follow-up for many fibrils by [Rutten et al. \(2019\)](#) subsequent down-drafting dark-fibril presence is evident in e.g., [Fig. 4 \(pdf 6\)](#) and [Fig. 8 \(pdf 10\)](#).

The physical reason for non-E $H\alpha$ retardation is the 10-eV size of the Ly α jump inhibiting collisional settling ([Carlsson and Stein 2002](#)). For He II 304 Å the underlying He I jump from $n=1$ to $n=2$ is twice larger and may cause similar non-E retardation for the He I top and ion populations in cooling after heating.

The fact that He II 304 Å similarly shows greyish blobs around surface network with coarse pattern correspondence to reversed $H\alpha$ may mean only that the $H\alpha$ scene effectively portrays previous He II temperatures, but it is also possible that also He II 304 Å itself stays overpopulated in gas that would already be too cool to show it per SE estimation. In the AIA 304 Å column of [Fig. 2 \(pdf 3\)](#) of [Rutten and Rouppe van der Voort \(2017\)](#) the heating-jet brightness lingers longer than in the 193 Å images when the $H\alpha$ -wing RBE is over and the very dark $H\alpha$ -core contrail takes its place.

So, possibly both $H\alpha$ and He II 304 Å live above their station. Of course they cannot match precisely. In propagating heating events such as spicules-II seen on the disk bright He II 304 will extend further than the dark RBEs and RREs in the outer $H\alpha$ wings (not seen with GONG), beyond where hydrogen ionizes. In the subsequent return phases bright He II 304 Å features likely sample hotter parts of cool-down recombination tracks also earlier and further from network than dark $H\alpha$ fibrils. The latter darken most close to the network launch sites.

Blinking [figures 11](#) and [12](#) indeed suggests, even at their low resolution and large noise, that the grey 304 Å patches generally extend well beyond the grey reversed- $H\alpha$ patches. Also, per [showex](#)²⁹ zoom-in many reversed- $H\alpha$ patches show bright grains at their centers, i.e., darkest fibril parts at the end of their retraction. The $H\alpha$ blurring applied in [figure 74](#) increased the overall anticorrelation shown there.

Showex timesliding of the AIA 304 Å sequence shows that the 304 Å grey-patch patterns are stable over 15 min, with rapid small-scale fluctuations (making me use the temporal mean in [figure 74](#) and fire detector construction). The rapid recurrence of on-disk spicules-II found by [Sekse et al. \(2013a\)](#) and [Rutten et al. \(2019\)](#) indeed suggests continual maintenance of heating-around-network patterns.

Chromosphere in AIA 131 Å

The next EUV diagnostic is AIA 131 Å in [figure 13](#). Blinking against 304 Å in [figure 12](#) shows remarkable similarity for the grey patches, quantified in the rightmost Strous diagram in [figure 74](#). These patches should be dominated by Fe VIII emissivity in this passband.

[Figure 6 \(pdf 7\)](#) of [Rutten and Rouppe van der Voort \(2017\)](#) shows that the characteristic coronal-equilibrium (CE) formation

²⁹ Blinker showex also accepts (e)ps or pdf figure files; I run it also from the command line piping to IDL with a script shown in my [pipeline manual](#).

temperatures for $H\alpha$, He II 304 Å and Fe VIII 131 Å are about 12, 50 and 400 kK, respectively, while for LTE Saha-Boltzmann (SB) equilibrium (at chromospheric density) they are only about 8, 16 and 56 kK, respectively.

The actual values must lie between these simplistic limits, with CE gaining validity over SB for increasing temperature and decreasing density, but in any case these SB–CE estimation ranges are enormous – whereas all three lines visibly conform in rendering the network chromosphere, the last two lines the closest but $H\alpha$ coarsely also in its network-imposed patterning.

This suggests overlap. My non-E suggestion is that PHEs (as spicules-II) heat and ionize the chromosphere around network to Fe VIII 131 Å emissivity, followed by along-the-track retraction cooling and recombination showing emission in He II 304 Å that may have non-E retardance, and then retarded \sqrt{e} darkening in $H\alpha$.

The quantification of 304–131 Å similarity in [figure 74](#) inspired the 304×131 Å image multiplication of my SDO fire detector, detailed in the caption of [figure 69](#).

Chromosphere around quiet network

In summary: I suggest that the rough similarity of the greyish scenes in $H\alpha$ ([figure 11](#)) and in He II 304 Å ([figure 12](#)) is because both lines sample essentially the same highly dynamic chromosphere around network, also seen in Fe VIII 131 Å ([figure 13](#)).

I conclude that the dynamic chromosphere around quiet network cannot be characterized by a single temperature, certainly not the SE equilibrium temperature for $H\alpha$ in a standard model. Everywhere around network PHE’s continually heat gas which then mostly flows back while cooling. The most likely agents are spicules-II observed as RBEs and RREs in $H\alpha$. These dynamic heating agents and their dark $H\alpha$ -core products constitute the grey patches making up most of the scenes in [figures 11–13](#) and seen best in [figure 69](#) and in the fire detector triple members of [figures 17–46](#).

The earlier Bifrost simulations of $H\alpha$ fibrils ([Leenaarts et al. 2012](#), [Leenaarts et al. 2015](#)) and accompanying ALMA scenes ([Loukitcheva et al. 2015](#)) lacked spicules-II and their fibrillar aftermaths around network, but recent addition of non-E retardation as well as ion-neutral ambipolar separation yields better numerical analogs ([Martínez-Sykora et al. 2020b](#), ?).

I expect that these will confirm that generally $H\alpha$ lives furthest above its station, in the form of dark cooling but non-E recombining fibrils producing opaque canopies around network that chart remembrance of much hotter things past. [Lockyer \(1868\)](#) named the chromosphere after the dark horse (helium his white one?).

Dark EUV features

The darkest patches between grey chromospheric network in the fire detector images match dark features in most of the AIA EUV images (blink [figures 12–15](#)). The AIA 335, 304, 221, 131, and 94 Å images show them similarly. They are sharper and best defined in AIA 171 Å but they correspond least in 193 Å (a brushfire example is specified in the caption of [figure 69](#)). They are not present (dark or bright) in the GONG $H\alpha$ image.

EUV darkness is either due to lack of EUV emissivity (as in coronal holes) or due to extinction (not “absorption”) from

bound-free out-of-the-passband scattering in overlying neutral gas ([Figure 10 \(pdf 12\)](#) of [Rutten 1999](#)). In such scattering the re-emitted photon is not only redistributed in direction but also in frequency, most likely to near the bound-free edge threshold far from the AIA passband, so that virtually every scattered photon diminishes the detected intensity for radiation originating deeper along the line of sight. Hence, dark features of this type require overlying gas containing sufficient neutral hydrogen and/or neutral helium (their visibility in 335 Å excludes ionized helium). The discordant non-visibility or flip-into-bright of these features in the 193 Å images then implies that hot gas contributing noticeable 193 Å emissivity overlies neutral gas affecting the others.

Chromosphere under brushfires

$H\alpha$ in [figure 11](#) differs markedly from the subsequent EUV images in that AIA 304 Å already shows bright brushfires as the hotter EUV diagnostics do: when blinking [figure 12](#) with [figures 13–15](#) these are remarkably co-spatial at least in bright footpoints – but GONG $H\alpha$ does not show them, also not in non-reversed [figure 10](#).

If this footpoint heating was bottom-up one might expect conspicuous features in $H\alpha$, but the scatter diagrams in [figure 74](#) display only slight-above-average GONG $H\alpha$ brightening where AIA 304 Å is brightest. Top-down particle beams may have less penetration into or heating of high-density $H\alpha$ gas, yet denser where it gets neutral with low electron pressure.

In addition, most of the campfire ROI cutouts in [figures 48–59](#) show extended diffuse 304 Å brightness around the small campfire that roughly duplicates diffuse brightness patterns in the hotter AIA cutouts, in particular the 193 Å ones. I attribute this difference with $H\alpha$ to how irradiation contributes ionization.

Hydrogen is mainly ionized by photoionization in the Balmer continuum from the deep photosphere, a very bland irradiator from below because the granulation pattern gets erased in 3D scattering through the upper photosphere ([Rutten and Uitenbroek 2012](#), [Leenaarts et al. 2012](#)).

In very hot instances collisional ionization takes over, but elsewhere the degree of hydrogen ionization is set by the $n=2$ population controlled by $Ly\alpha$, with Balmer continuum NLTE as instantaneous SE-obeying modifier. It is the retarded settling of $Ly\alpha$ that governs retarded non-E hydrogen recombination usually called “non-E ionization”. Where $H\alpha$ lives far above its station from slow $Ly\alpha$ settling, so does HI ionization and with it the HI free-free continuum dominating the ALMA mm passbands ([Figure 1 \(pdf 4\)](#) of [Rutten 2017b](#)).

In contrast, He I ionization also senses irradiation from above, making coronal holes visible in He I 10830 Å and He II 304 Å. This may occur via downward EUV irradiation ionizing He I (edge at 504 Å) and exciting He II 304 Å, or from ionizing He II (edge at 228 Å) with cascade-recombination through He II 304 Å.

When such EUV irradiance patches ionize He I in cool or cooling gas with slow He I $n=1-2$ settling to the Boltzmann ratio, the resulting He II 304 Å emissivities may also maintain non-E-retarded memorial boosting.

He II 304 Å in a well-sampled brushfire

Figure 1 (pdf 2) of Rutten and Rouppe van der Voort (2017) targeted active bipolar network with a patch of overlying small EUV-bright loops constituting a brushfire best seen in the last 193 Å image. This is one of the combined SST–IRIS datasets made available by Rouppe van der Voort et al. (2020).

This brushfire appeared as a double set of 15-arcsec EUV-bright arches connecting multiple patches of active bipolar network underneath. Most brushfires in the triple-member 193 Å images here show single sets of such arches.

The 304 Å and 193 Å images in that figure and the corresponding cutout sequences in the subsequent Figure 2 (pdf 3) show that the 304 Å bright patch conforms roughly to the 193 Å bright patch but with sharper bright and dark features, many with filamentary shape.

The IRIS 1400 Å slitjaw image in the first figure and cutouts in the third column of the second figure show roughly similar bright and dark patterns as 304 Å, less bright but sharper.

With 1400 Å “bright” I mean the grey patches, excluding the brighter roundish grains which are surface MCs that are hole-brightened in the 1400 Å continuum as in figure 73 and also seen as bright points in the H α blue-wing cutouts in the first column, unless covered by the dark RBE-like jet that is the topic of that study. Where these shine through the grey 1400 Å patches called bright here the latter must be optically thin.

For the times of rows 4 and 6 in the second figure (pdf 3) the next figure (pdf 4) adds panels sampling Ca II 8542 Å and 171 Å. The Ca II 8542 Å blue-wing panels shows the MCs also, hole-brightened by less collisional broadening and superposed on reversed granulation without shielding.

The 1400 Å similarity to the 304 Å scene comes from the contribution of the Si IV lines in the IRIS passband. The He II and Si IV ion occurrence temperatures overlap pairwise in the CE and SB limits in Figure 6 (pdf 7) of Rutten and Rouppe van der Voort (2017). The adjacent Figure 7 (pdf 7) holds for the SB limit which is better for hot dense gas. The He II and Si IV humps there occupy the same temperatures but with 10^3 extinction ratio from the abundance ratio. Indeed, the 1400 Å and 304 Å features in the quoted Figure 1 (pdf 2) and Figure 2 (pdf 3) agree when regarding the former as much optically thinner than the latter.

The bright fine structuring, seen best in the better-mapping 1400 Å images, does not duplicate the more diffuse 193 Å scene so that EUV irradiation is not the only agent. Part of the fine-scale brightening is heating from below as evident in the extending RBE-like jet in the upper rows which is dark in the first column, bright in 1400 Å, and produced the subsequent dark H α -core contrail in the second column. There are a few more such upward-heating features that are dark in the first column and bright in 1400 Å, but most smaller grey 1400 Å patches in the lower rows may well be due to downward particle heating. They appear smaller than in larger-opacity 304 Å and indeed lie around the yet brighter grains that mark footpoint MCs into which the accelerated particles should funnel down.

Appendix C: Epilogue on publishing

During this effort I wondered how to publish it. Formally, in a regular refereed “journal”? The most fitting seemed *Solar*

Physics but last year Springer put me into a depression by mishandling Rutten (2019). I wrote that away by posting my grudges in a dozen bitter Springer nasturtia.

Also, “publish or perish” is no longer an issue for me – *alea iacta est*.³⁰

I then wondered about starting my own institute series, in line with starting my own institute when Utrecht University killed 370-year-old Utrecht astronomy – including Dutch solar physics. I arrived too late in this 370-year timespan to publish in French in the *Recherches Astronomiques de l’Observatoire d’Utrecht* and also for the subsequent switch to German as principal science language³¹, but in time to publish in the *Bulletin of the Astronomical Institutes of the Netherlands* when institute publications were still mainstream platforms³².

I am also much impressed by the 250 citations of Mats Carlsson’s 1986 exemplary Uppsala report describing MULTI, more than for our most boring (since nonsolar) MULTI-based Carlsson et al. (1994) which remains my most-cited publication.

Another inspiring example are Edsger Dijkstra’s personal writings found when I wondered why IDL counts fingers from 0 to 9.³³

I then decided on this institute-report format for the present analysis, and hopefully more.

In hindsight my recent single-author publications might also have been Lingezicht reports without further ado. However, I must concede that the outstanding referee and the attentive scientific editor of Springer-mishandled Rutten (2019) significantly improved that conference³⁴ write-up.

Likewise, I must add that I much appreciate A&A–EDP’s efficient publication handling, including helpful language editing and not molesting my hyperlink macros as other astronomy publishers including ApJ do. I also like the aa.cls latex style and used it here by starting with my report example for students as template. Naturally I also appreciate A&A’s fee waiver for Lingezicht Astrophysics since Utrecht’s demise. However, I judged the material presented here too provincial, too detailed and too inconclusive for submission to A&A – too much honor for a single non-validated image even though press-released.

I intend to post these reports on my website³⁵. They are in good company there since my most-read publication (Rutten 2006) and my most-used publication (Rutten 2003) were both only self-posted, successfully relying on Google’s indexing (plus ADS for the second) for spreading. Such posts may be kept “living” with updates. I did for Rutten (2006) but servicing Rutten (2003) remains overdue.

³⁰ Six years Latin in high school did not forward my career, nor did five years classical Greek in which Caesar probably said this.

³¹ For a brilliant example see Kees de Jager’s scathing review (pdf 1) of “Physics of the solar chromosphere” of ADS-misattributed Athay and Thomas (1961) in ADS-mislabeled Thomas and Athay (1962), ending here (pdf 1) in ADS-mislabeled Waldmeier (1962).

³² Until new BAN editor Stuart Pottasch joined national journals into A&A.

³³ Needing $nx/(nx-1)$ and $nx+1$ corrections in SDO image axis labeling as in `xaxis=(indgen(nx)*float(nx)/(nx-1)-(nx+1)/2.)*CDELTA1+XCEN` for solar X. Do you?

³⁴ IAU GA in 2018 at Vienna – my last pre-covid non-line meeting. Since then I became the only solar physicist always working in the institute office.

³⁵ I did with this one here and update it since as specified in the version history.

I may also post these reports at arXiv for ADS access, citing, and persistence beyond my website and me.³⁶ Such posts may also be kept alive.³⁷

Obvious advantages of self-publication are that I may embellish, pontificate, expostulate, footnote-comment, caption-didact, hyperlink, joke and be personal (first names) just as I like without fearing editors, that I may skip reviewing literature without fearing citation-desiring referees, that all my fancy hyperlinks keep working unmolested, that I don't have to minimize figure sizes and numbers in fear of page limits, and that I can use formats I like³⁸ as well as keep figures separate at the end (for parallel viewing) and full-page (for blinking).

An obvious disadvantage is that my Hirsch index growth may suffer, but at the median of senior colleagues in [Fig. 1 \(pdf 8\)](#) of [Rutten \(2018\)](#) I cherish mediocrity.

After I decided on its format this report grew considerably in content, hyperlinks, references, links to published figures, footnotes, appendices (new to me), and very many figure pages³⁹, notwithstanding considerable shortening by shunting detailed descriptions of my [SDO-STX alignment pipeline](#) and my [showex.pro](#) browser to future Lingezicht reports.

Acknowledgments

I am indebted to Alan Ferguson for alerting me to the Solo press conference and to Ron Moore for correcting bushfire to brushfire.

SDO is a NASA mission of which all data are Alan-Title-style exemplary public, without any reservation whatsoever, and made easily accessible and ready-for-science through extensive and commendable efforts by the Stanford (HMI, JSOC) and LMSAL (AIA) teams. I regularly and reliably obtain and appreciate additional help from Phil Scherrer, Arthur Amezcua, Mark Cheung, Greg Slater, John Serafin, Sam Freeland.

Solar Orbiter is a space mission of international collaboration between ESA and NASA.

As always I made much use of the splendid SolarSoft and ADS libraries.

Version history

July 16, 2020 – Solar Orbiter press conference. Started scene search in SDO.

August 3, 2020 – eureka: at last found Solo campfires in SDO/AIA EUVs.

August 31, 2020 – initial version posted on website and arXiv; [arXiv version](#) without [epilogue](#). Since then the [website version](#) is “live” latest.

September 14, 2020 – [arXiv version 2](#): Solo caveat under [figure 1](#), twenty new “other scene” blink pairs in [figures 17–46](#), “bushfire” corrected to “brushfire” ([footnote 6](#)), better fire detector by basing thresholds on quiet network ([figure 69](#)), AIA 304–131 Å driftplot added ([figure 75](#)), reference to [Falconer et al. \(1998\)](#), much text re-written and added.

September 15, 2020 – reference to [Alissandrakis \(2019\)](#).

³⁶ In our bitter dispute last year Springer’s manager of *Solar Physics* wrote that arXiv-only “publication” is viable but undesirable. Boycotting hybrid double-dipping predator publishing now seemed so desirable to me that I forsook my principle of archiving refereed only. Colleagues who saw the present report as manuscript advised arXiv; I did ([arXiv 2009.00376](#)) but without this epilogue.

³⁷ I soon revised the arXiv upload. Differences between arXiv versions can be inspected by downloading their source materials and running `latexdiff`.

³⁸ Including Eugene Avrett’s one-point-per-paragraph style in dog-eared VAL (1973, 1976, 1981) preprints, the only paper ones still on my desk.

³⁹ Hoping that easy blinking makes them actually get inspected. In a formal publication the 75 figures here, most full-page and all adorning the single press-release image in the first, would probably editorially be made “online material” (oldfashionedly since printing cost and volume thickness are no longer issues for publications that are themselves online material). I rarely inspect such if it requires more than one-click access – which I implemented for figure panel blinkers in [Rutten et al. \(2019\)](#), similar to my direct [cited-page openers](#) also used here (for the non-Mac-challenged). I also suspect that in a formal publication these 39 footnotes would be editorially scrapped.

September 20, 2020 – improvements, this history, \ref links blue for dichromats.

September 25, 2020 – more fluxtube review below [figure 73](#).

October 19, 2020 – brushfire detail at the end of [appendix B](#).

November 25, 2020 – H α sequence diagram added to [figure 74](#).

December 4, 2020 – more references, particle beams after [Frogner et al. \(2020\)](#).

December 24, 2020 – “St. Elmo’s fires”, [arXiv version 3](#).

July 21, 2021 – more informative reference format (but shifting figure pages by one compared to the latest arXiv version)

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List of Figures

1	Press-release SoLO 174 Å image	19	43	South-pole HMI magnetogram at maximum	61
2	Full-disk HMI magnetogram	20	44	South-pole AIA 193 Å image at minimum	62
3	Full-disk AIA 1600 Å image	21	45	South-pole SDO fire detector at minimum	63
4	Full-disk AIA 304 Å image	22	46	South-pole HMI magnetogram at minimum	64
5	Full-disk AIA 171 Å image	23	47	Campfire cutout locations in the SoLO image	65
6	Full-disk AIA 193 Å image	24	48	ROI-1 cutout assembly	66
7	Solo-field HMI magnetogram	25	49	ROI-2 cutout assembly	67
8	Solo-field AIA 1700 Å image	26	50	ROI-3 cutout assembly	68
9	Solo-field AIA 1600 Å image	27	51	ROI-4 cutout assembly	69
10	Solo-field in GONG H α image	28	52	ROI-5 cutout assembly	70
11	Solo-field in reversed GONG H α image	29	53	ROI-6 cutout assembly	71
12	Solo-field AIA 304 Å image	30	54	ROI-7 cutout assembly	72
13	Solo-field AIA 131 Å image	31	55	ROI-8 cutout assembly	73
14	Solo-field AIA 171 Å image	32	56	ROI-9 cutout assembly	74
15	Solo-field AIA 193 Å image	33	57	ROI-10 cutout assembly	75
16	Pixel intensity histograms	34	58	ROI-11 cutout assembly	76
17	AIA 193 Å image in the North-East	35	59	ROI-12 cutout assembly	77
18	SDO fire detector in the North-East	36	60	Brushfire cutout locations in the SoLO image	78
19	HMI magnetogram in the North-East	37	61	ROI-A cutout assembly	79
20	AIA 193 Å image in the South-West	38	62	ROI-B cutout assembly	80
21	SDO fire detector image in the South-West	39	63	ROI-C cutout assembly	81
22	HMI magnetogram in the South-West	40	64	ROI-D cutout assembly	82
23	AIA 193 Å image in the South-East	41	65	ROI-E cutout assembly	83
24	SDO fire detector image in the South-East	42	66	All cutouts in HMI magnetogram	84
25	HMI magnetogram in the South-East	43	67	All cutouts in AIA 193 Å image	85
26	Solo-field AIA 193 Å image in 2019	44	68	All cutouts in AIA 131 Å image	86
27	Solo-field SDO fire detector image in 2019	45	69	All cutouts in AIA 304×131 construct	87
28	Solo-field HMI magnetogram in 2019	46	70	Tile shifts 1700–1600 Å	88
29	Solo-field AIA 193 Å image in 2018	47	71	Zonal azimuthal tile-shift averages	89
30	Solo-field SDO fire detector image in 2018	48	72	Tile shifts 1700–1600 Å after heightdiff	90
31	Solo-field HMI magnetogram in 2018	49	73	MC brightening at 1700 and 1600 Å	91
32	Solo-field AIA 193 Å image in 2017	50	74	Strous diagrams	92
33	Solo-field SDO fire detector image in 2017	51	75	SDO cross-alignment results	93
34	Solo-field HMI magnetogram in 2017	52			
35	North-pole AIA 193 Å image at maximum	53			
36	North-pole SDO fire detector image at maximum	54			
37	North-pole HMI magnetogram at maximum	55			
38	North-pole AIA 193 Å image at minimum	56			
39	North-pole SDO fire detector image at minimum	57			
40	North-pole HMI magnetogram at minimum	58			
41	South-pole AIA 193 Å image at maximum	59			
42	South-pole SDO fire detector image at maximum	60			

Figure blinking by page flipping

Viewer-dependent; try single-page, fit-to-page, full-page, full-screen, presentation mode, thumbnail panel, left-right, up-down, page up-down.

- Gnome evince: zoom-in (CTRL +), page-blink with up-down in the thumbnail side panel or full-page and left-right;
- Acrobat acroread: full-page (CTRL L), zoom-in (CTRL +), blink left-right;
- Ubuntu qpdfview: full-screen, zoom-in (CTRL right), blink left-right;
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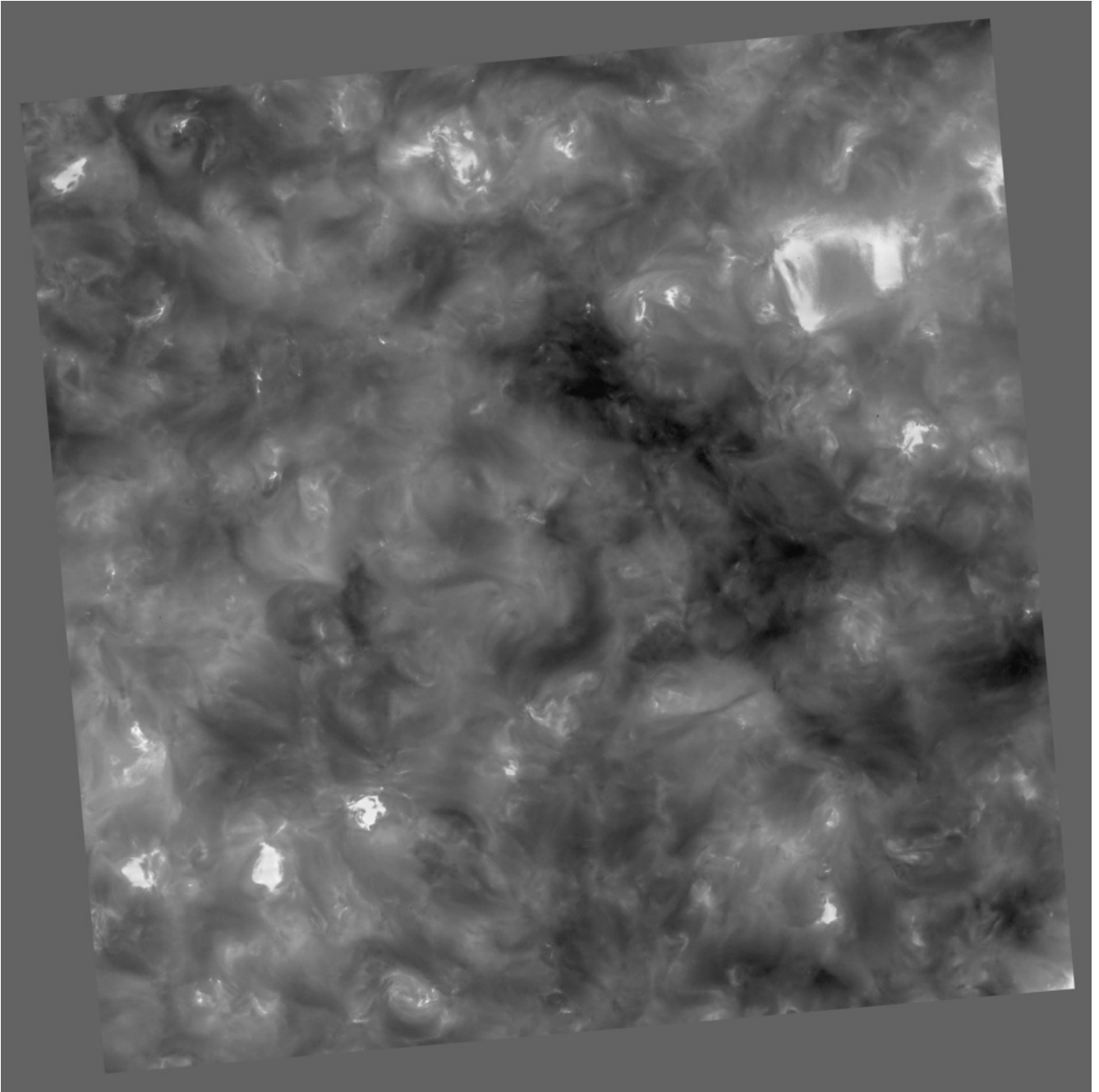


Fig. 1. Press-release Solo 174 Å image, roughly rotated to solar (X, Y) as seen from SDO. After my long search for it this scene is burned into my brain. “Solo campfires” appear as tiny bright stalks; zoom-in may help to spot them. It is the sole Solo input for this report; all other images are from SDO, plus one GONG $H\alpha$ image.

Caveat disclaimer: EUI PI David Berghmans reprimanded me later that this image “is not properly validated” and showing it here is “unfair to the intrinsic quality of the EUI instrument” – but it serves here only to display the “campfires” shown and advertised during the Solo press conference, and as proof that I eventually did find this non-specified Solo scene in SDO (compare with [figure 15](#)). Proper validation may make this image yet better and enable proper axes, but will not affect any other image here nor SDO campfires in these (which by existing guarantee that the Solo ones can’t validate away).

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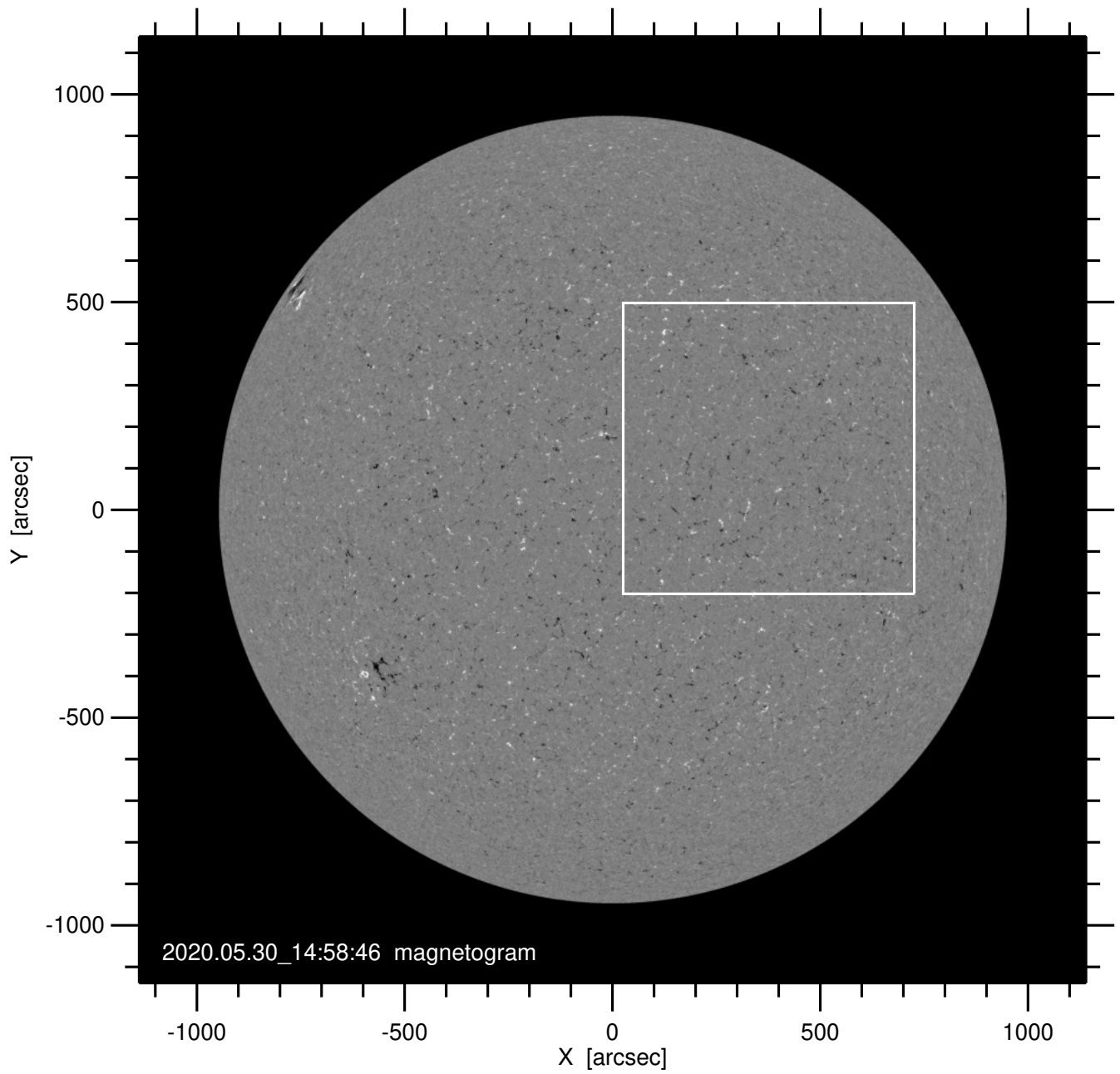


Fig. 2. HMI magnetogram at best-match time, with the selected field marked by the white frame. It contains the SolO field. It did not contain major activity, present here only towards the East limb (where IRIS pointed that day, still farside for SolO).

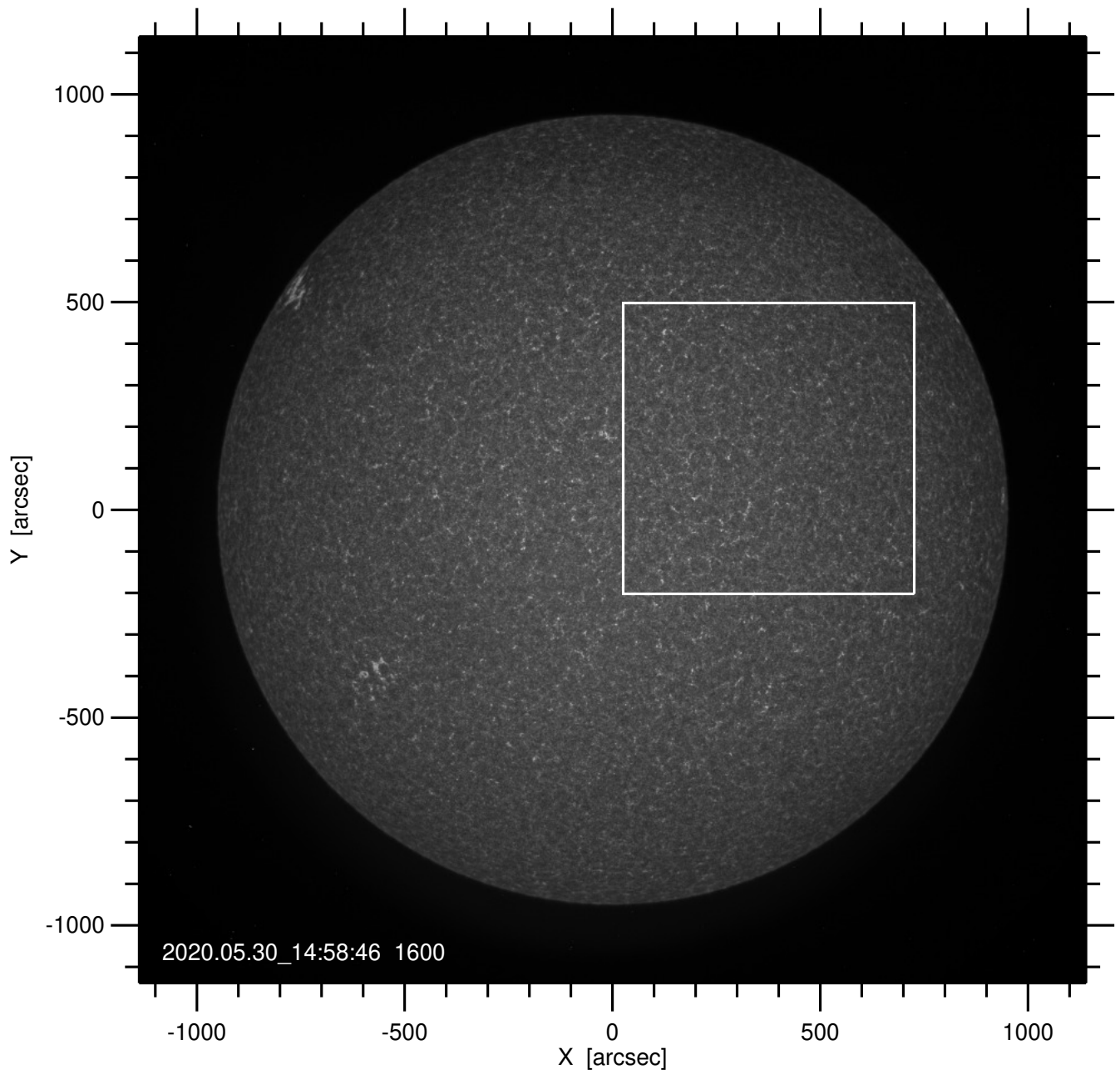


Fig. 3. AIA 1600 Å image at best-match time. It outlines the magnetic network seen in [figure 2](#) very well as small bright grains obeying [figure 73](#).

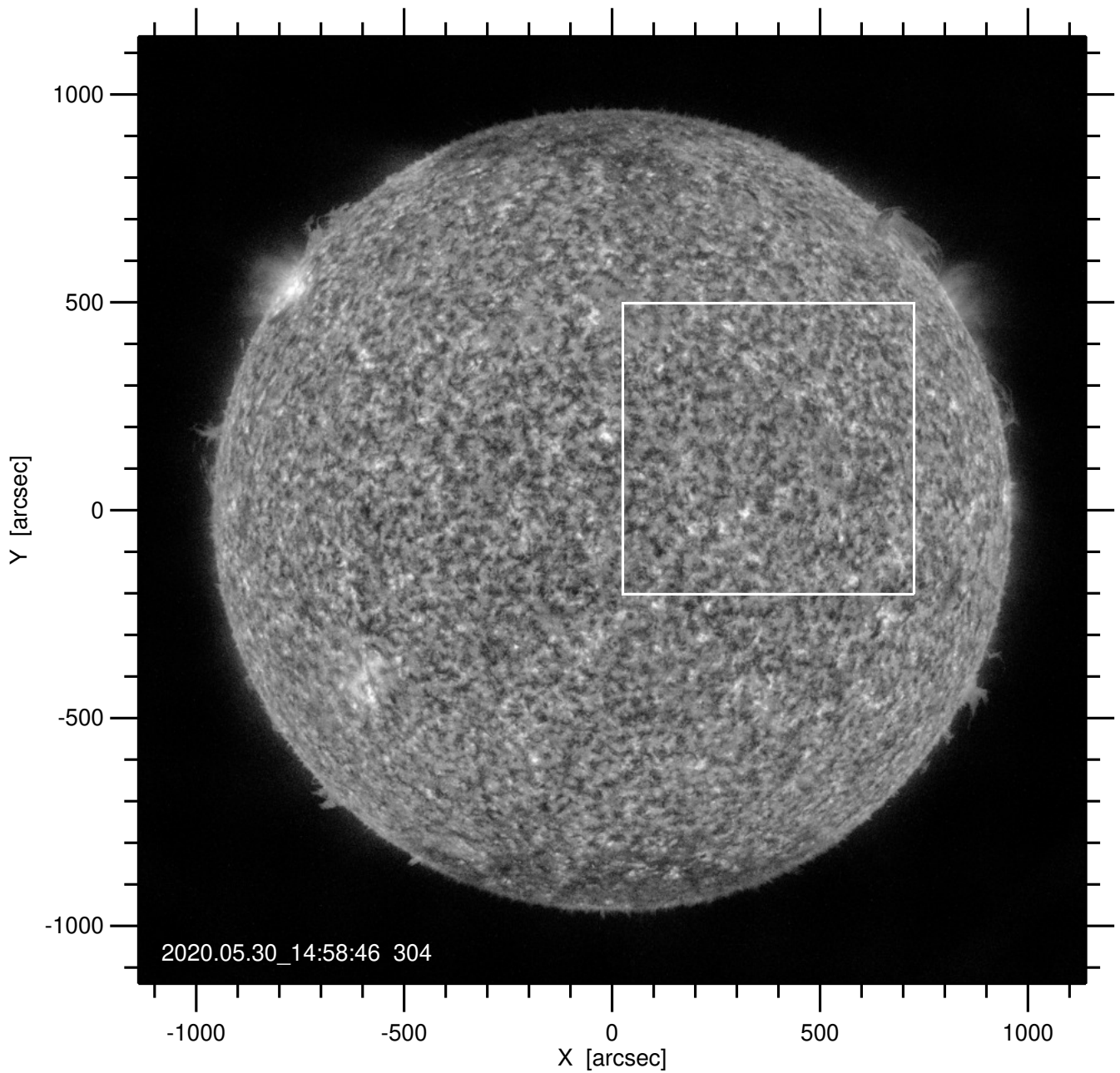


Fig. 4. AIA 304 Å image at best-match time. The dense coverage by grey patches is addressed in [appendix B](#). They show the chromosphere with traditional “transition region” temperatures but also visible in $H\alpha$. Notice small brighter patches called “brushfires” below, as coyly as “campfires” but with language correction from Ron Moore ([footnote 6](#)).

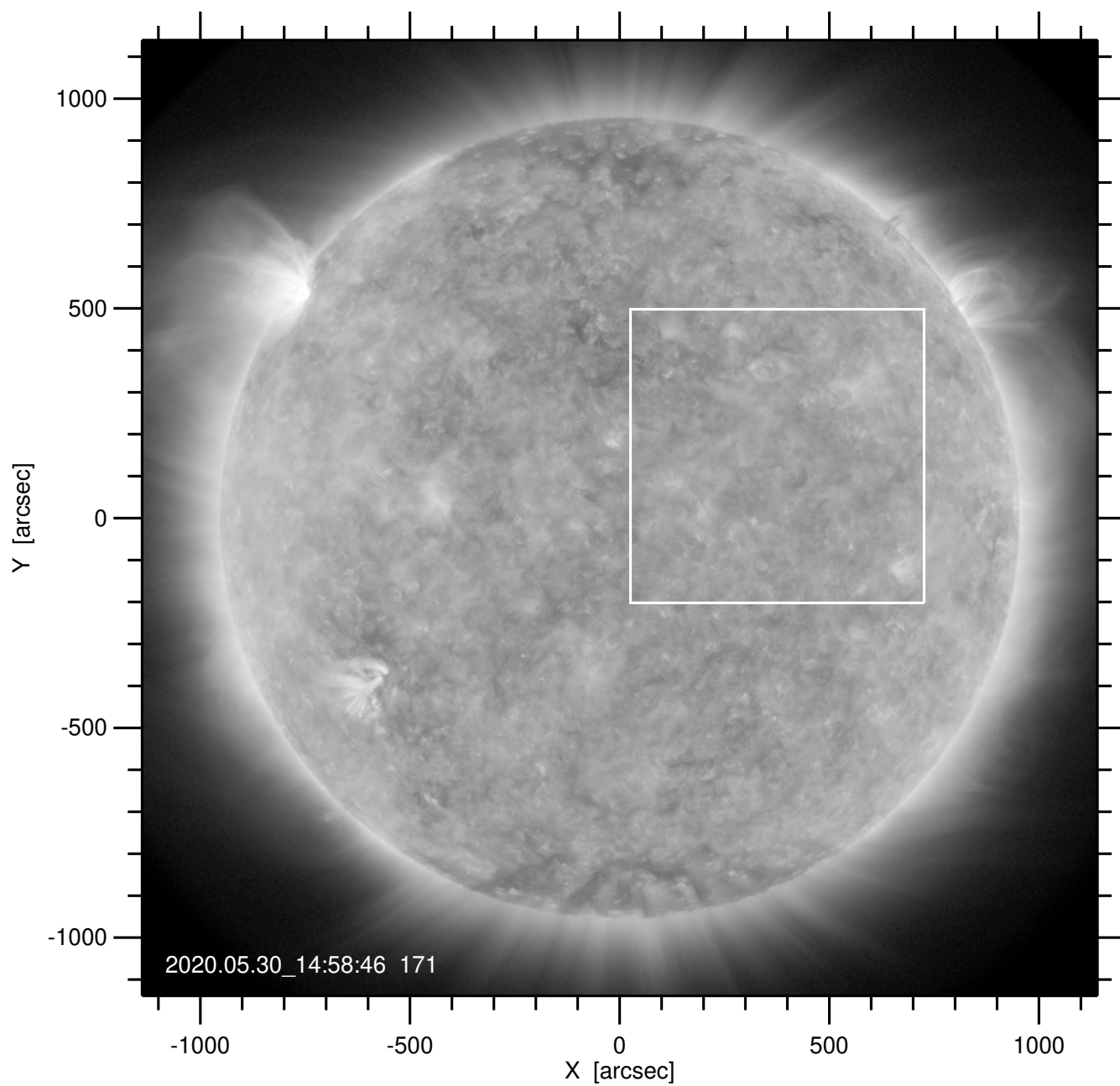


Fig. 5. AIA 171 Å image at best-match time. Obviously this AIA diagnostic is the best to show coronal connectivity and non-nearby-connectivity in polar plumes.

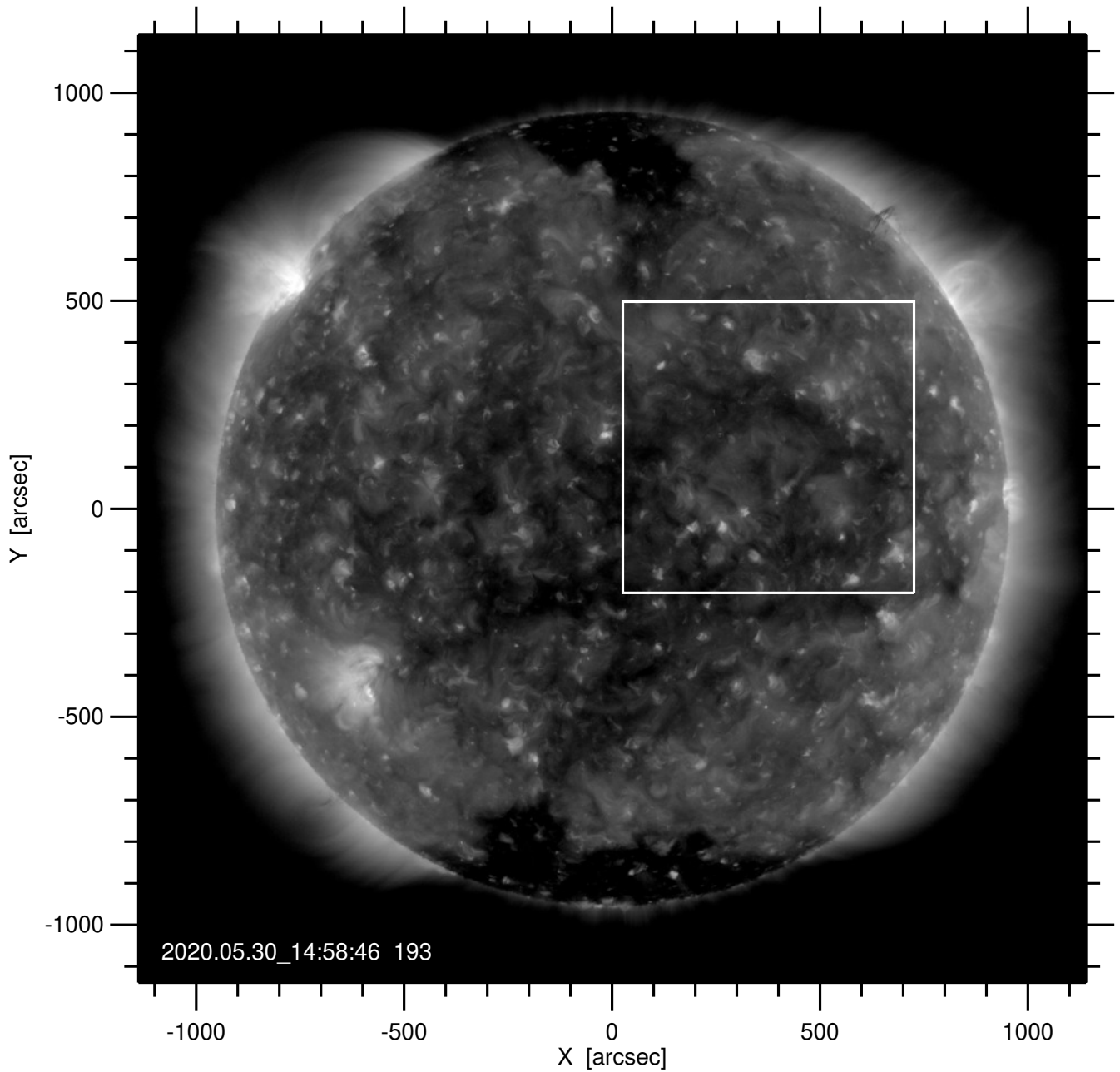


Fig. 6. AIA 193 Å image at best-match time. This AIA diagnostic also shows coronal connectivity but outlines coronal holes (here especially at the poles) and similar areas of less optical thickness in hot coronal emissivity clearer. “Fires” (campfires or brushfires) stand out very well. If you blur your vision the pattern within the box and the scene in [figure 1](#) agree, demonstrating that I did find the latter in SDO images – eventually. In hindsight, I mistakenly searched AIA 171 Å movies that looked as the preceding figure; with this diagnostic I might have succeeded faster.

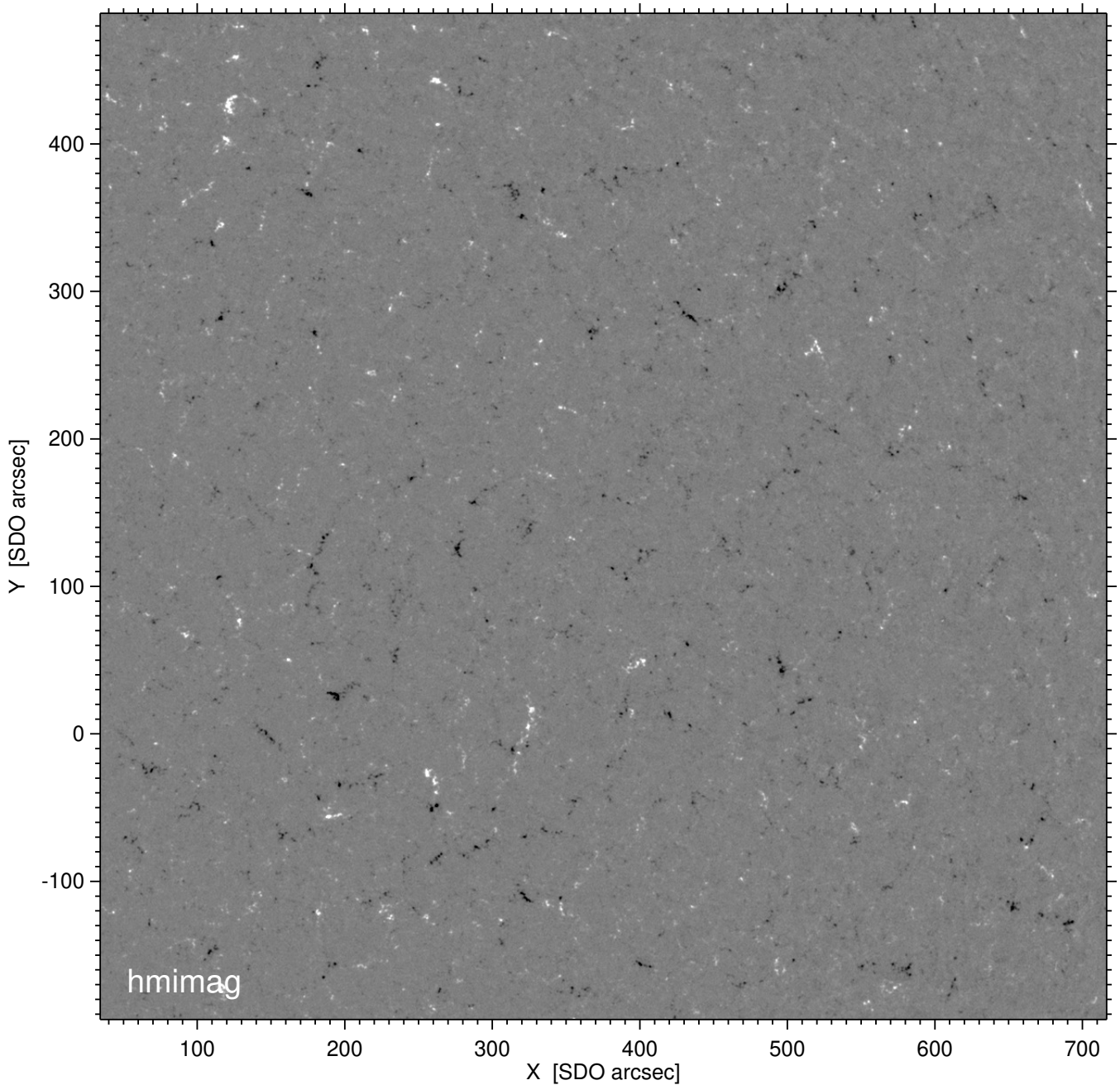


Fig. 7. The SDO field at best-match time in the downloaded HMI magnetogram sequence. The greyscale is clipped at apparent flux density $B_{app}^{HMI} = \pm 200 \text{ Mx cm}^{-2}$ to enhance the visibility of the network fields occupying this quiet area. The subscript *app* stands for “apparent” following [Lites et al. \(1999\)](#) to emphasize that while these units formally equal Gauss units, the actual intrinsic field strength in the magnetic concentrations (MC) charted here is much higher, of kilogauss amplitude. The superscript *HMI* specifies the apparent/intrinsic ratio as a specific instrument property. The small black and white (“bipolar”) MCs are roughly arranged in the apparent “network” incompletely outlining supergranular convection cells (e.g., [Schrijver et al. 1997](#)). The grey internetwork in between shows just noise due to low sensitivity. Charting internetwork fields needs higher sensitivity, as with Hinode/SP (e.g., [Lites et al. 2008](#)). The area is quiet and generally mixed-polarity. On small scales there appear to be many monopolar clusters of a dozen or so same-color grains, but with better magnetic sensitivity these likely will show opposite-polarity concentrations as well. In higher resolution observations all such MCs are no longer pointlike but have fast-varying morphology following local intergranular-lane dynamics (e.g., the SST “flowers” of [Berger et al. 2004](#)).

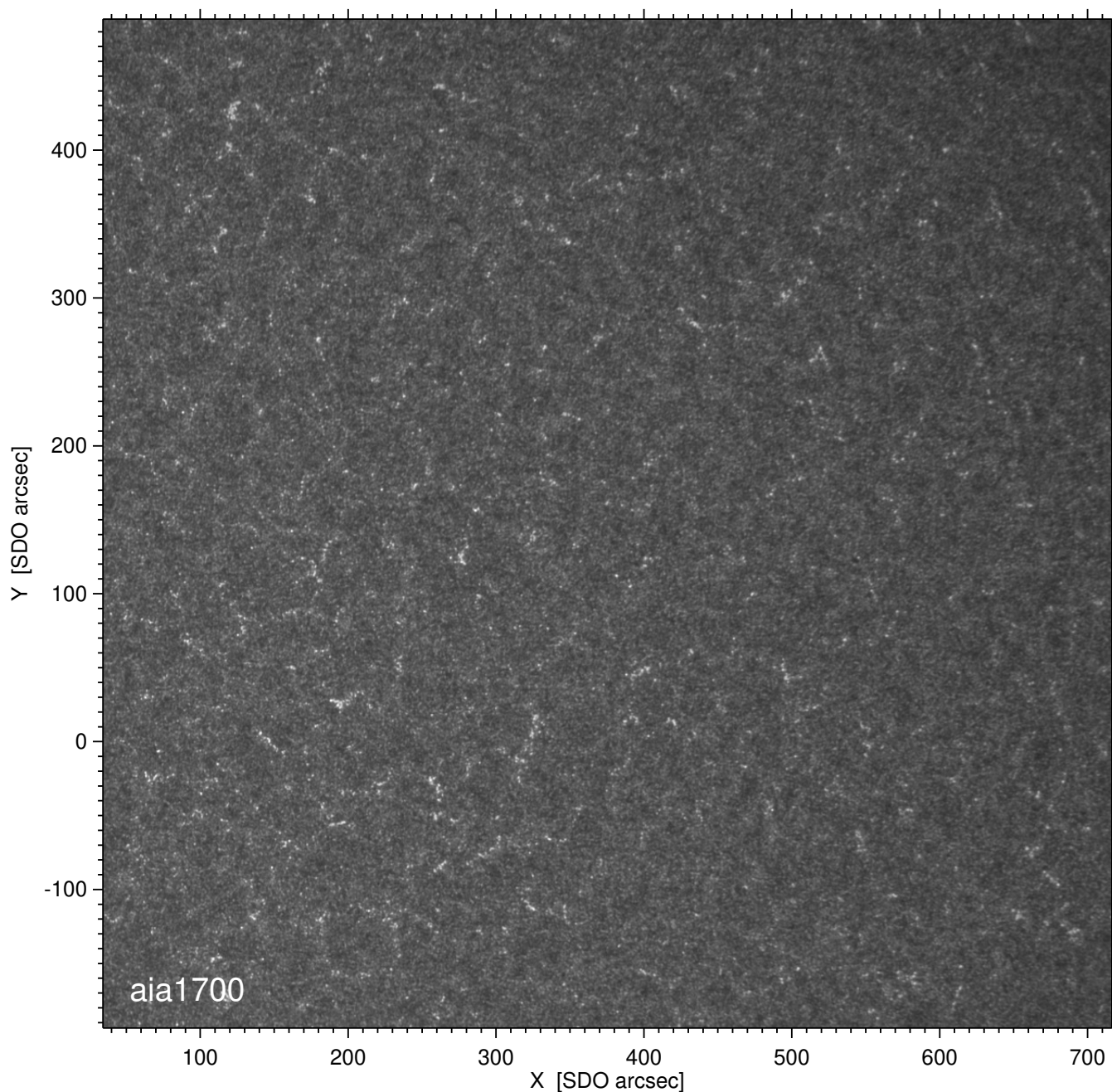


Fig. 8. The SDO field at best-match time in the AIA 1700 Å image. The greyscale shows the square root of the intensity after clipping the brightest pixels in the 15-min sequence. The scene shows “bright points” closely corresponding to the MCs in the preceding figure and roughly arranged in quasi-cellular supergranulation-driven network patterns with greyish internetwork shock interference patterns inside. When playing the sequence as a movie the bright points remain fairly stationary while the shock patterns move around very fast in erratic fashion. The latter are not discussed here but were brilliantly identified by [Carlsson and Stein \(1997\)](#) as clapotispheric shocks ([Figure 12 \(pdf 8\)](#) of [Rutten 1995](#)) driven and patterned by *p*-mode interference.

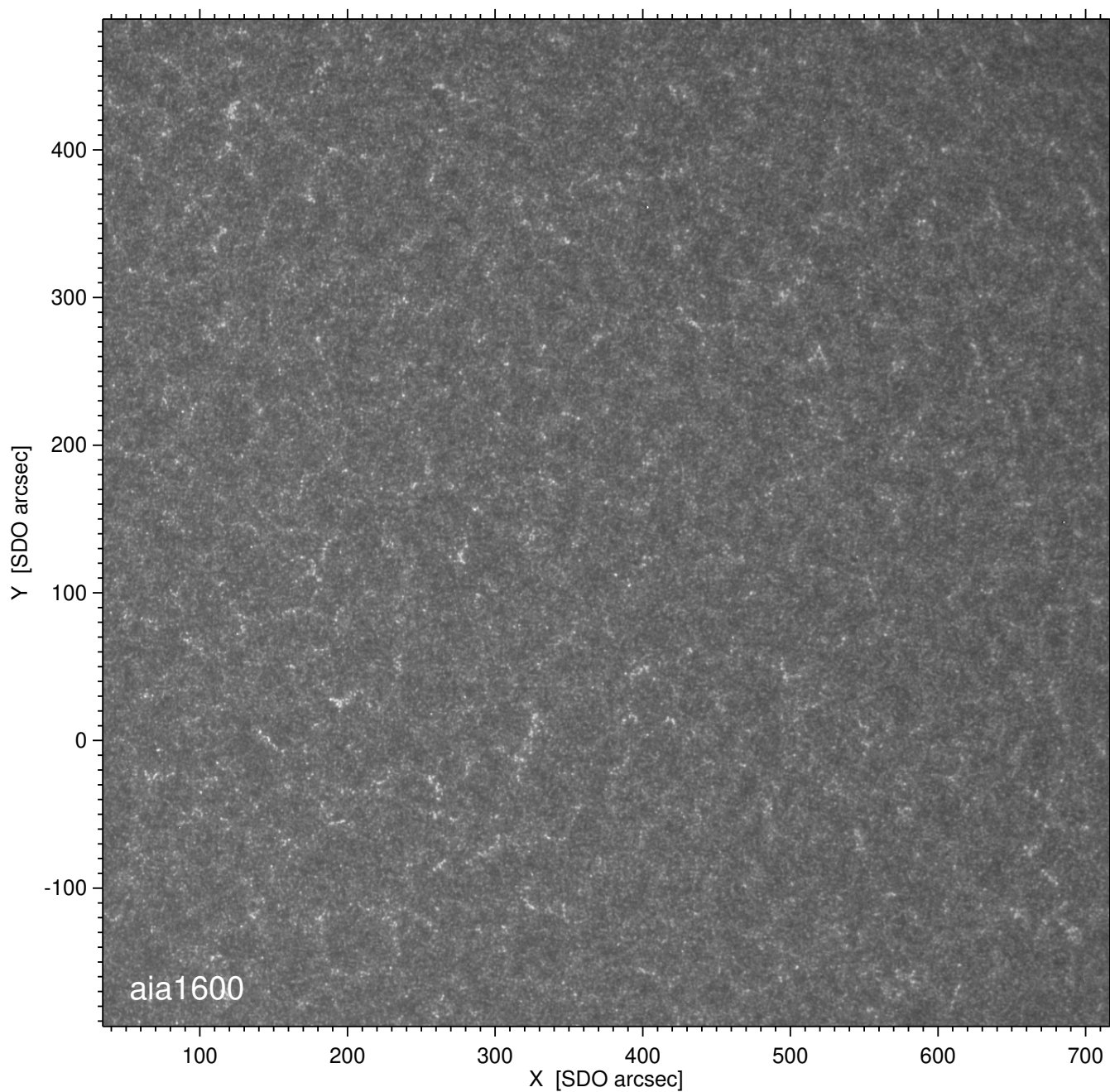


Fig. 9. The SDO field at best-match time in the AIA 1600 Å image. The greyscale shows the square root of the intensity after clipping the brightest pixels in the 15-min sequence. The scene is very similar to the one in the 1700 Å image in preceding [figure 8](#), but in blinking at sufficient zoom-in the 1600 Å bright points appear shifted limbward with different morphology. This is detailed in [appendix A](#) and in [figure 73](#) with a review-style caption.

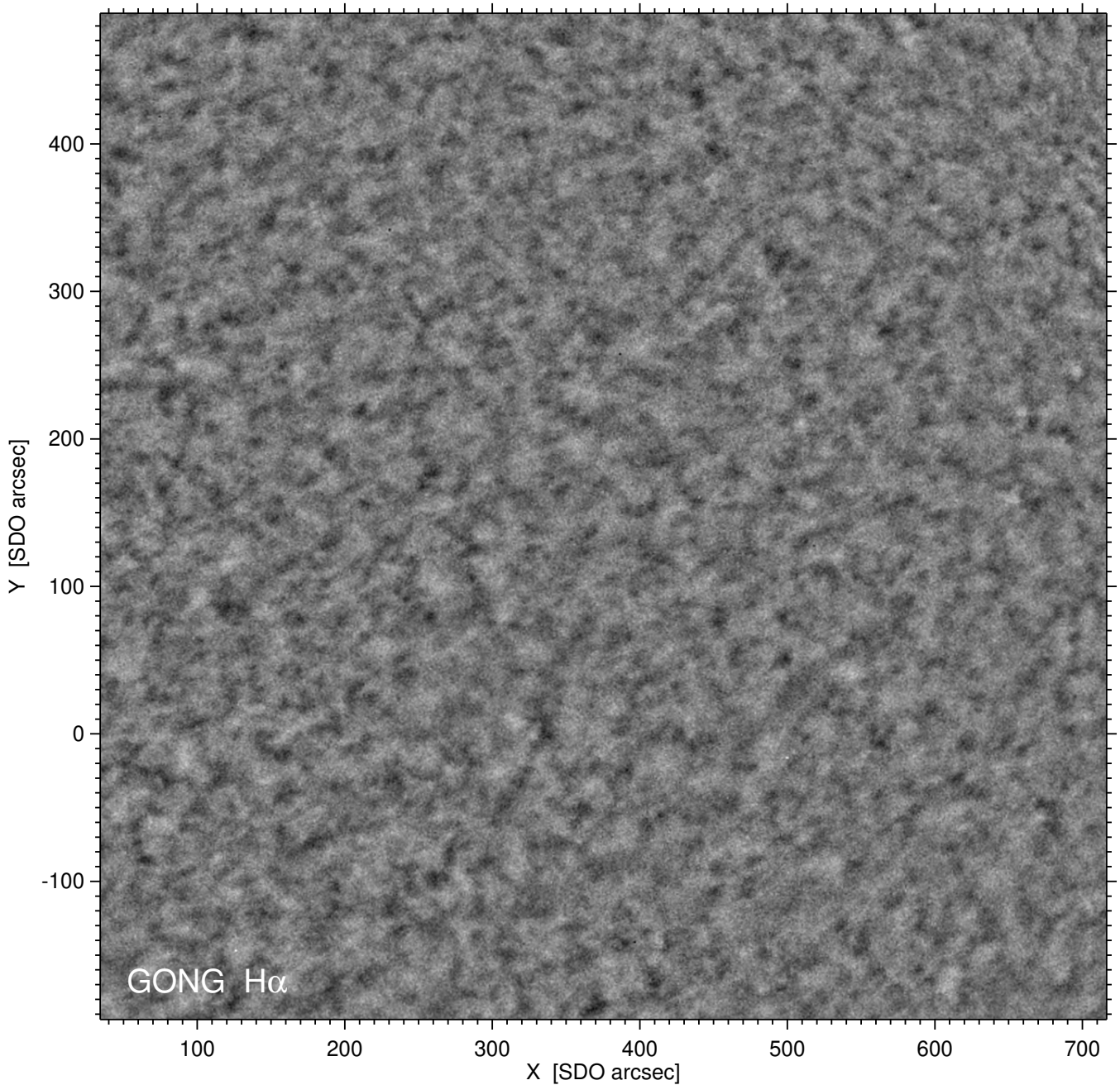


Fig. 10. The SDO field at best-match time in a simultaneous Big Bear GONG $H\alpha$ image. The cutout is bytescaled after severe clipping and limb darkening removal. The angular resolution is too low to show that the darker, roughly linear, patches are made up of fibrils. Higher-resolution $H\alpha$ imaging would show that these emanate from network. Yet-higher-resolution outer-wing $H\alpha$ imaging would show slender recurrent RBEs and RREs emanating further from network (Figure 4 (pdf6) of Sekse et al. 2013b). Appendix B argues that the latter produce the former. The plans for a DOT-clone GONG successor (Fig. 13 (pdf8) of Hill et al. 2019) include $H\alpha$ tuning to the outer wings. The present GONG network takes full-disk images of this quality sampling the wide core of $H\alpha$ at 20 s or slower cadence with 24/7 coverage about 90% since 2009, before SDO. The resolution is nominally twice worse but worsens further by station-dependent and time-dependent seeing also causing rubber-sheet warping. See the [GONG \$H\alpha\$ fact sheet](#).

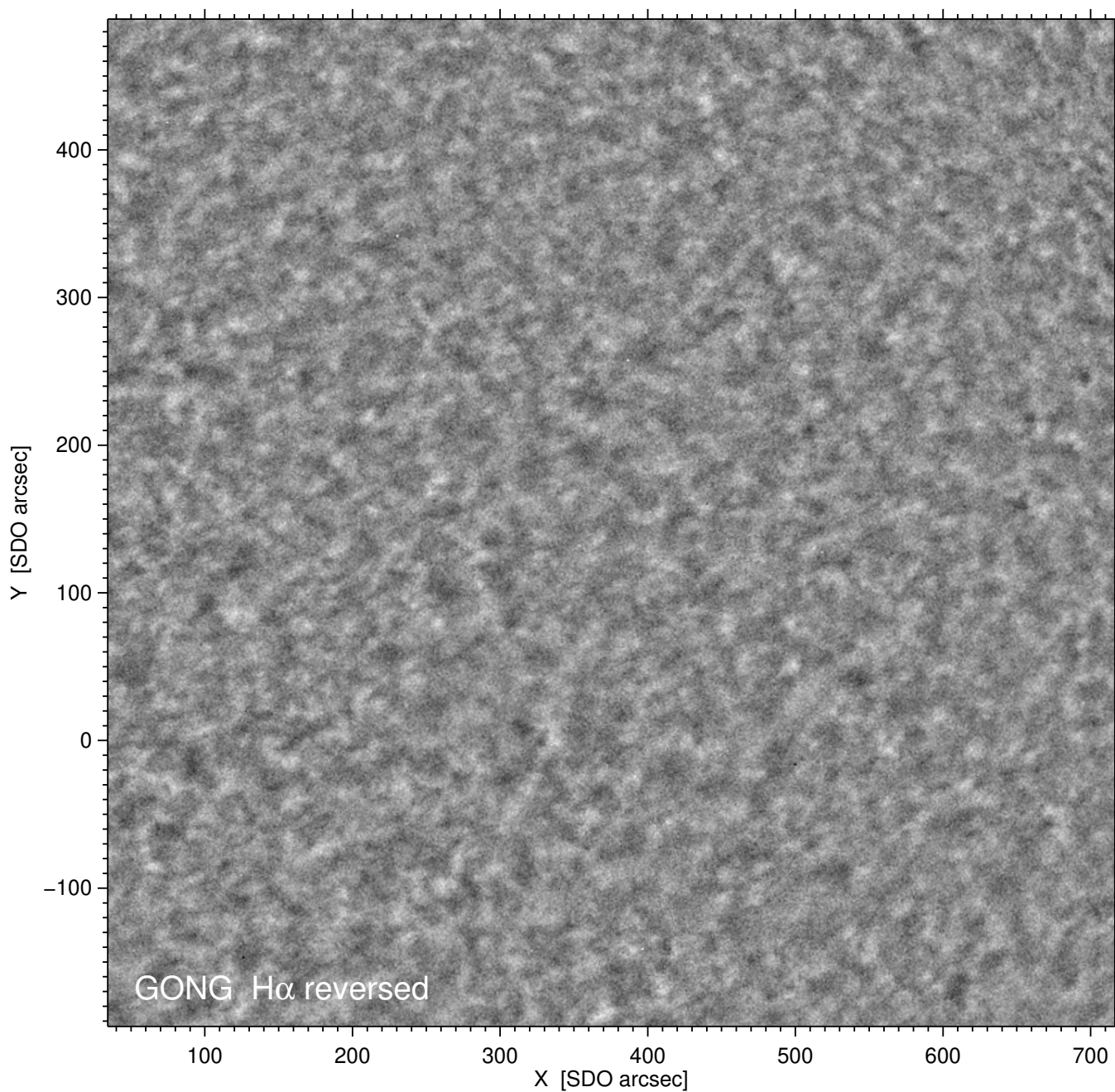


Fig. 11. The same GONG H α image as in preceding [figure 10](#), but with the greyscale reversed. This image is inserted here to facilitate blinking to the next (AIA 304 Å). How to blink pdf pages in a pdf reader is treated on [page 9](#). When you blink them the scenes appear to jump due to your eye detecting patch size differences but they are actually well aligned. This comparison is striking and discussed in [appendix B](#).

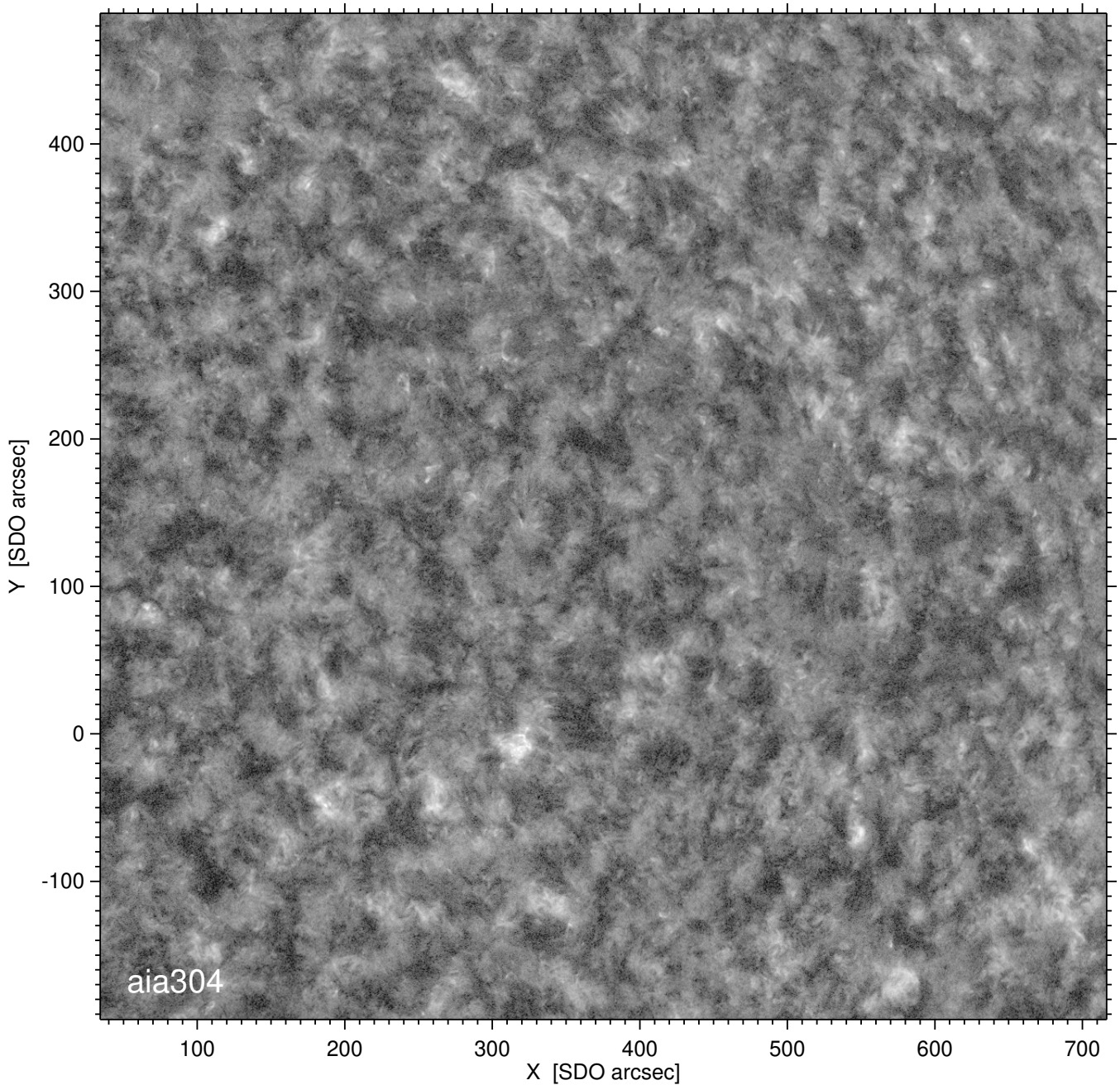


Fig. 12. The SDO field at best-match time in the AIA 304 Å image. The greyscale shows the logarithm of the intensity in rescaling with [sdo_intscale.pro](#) and clipping the brightest pixels in the 15-min sequence. Unfortunately, the AIA 304 Å channel lost much sensitivity over the years; initially the signal-to-noise was much better. The campfires detailed in [section 6](#) are not very obvious but blinking against the next images shows they are here too. Their presence here and in the next AIA 131 Å image led to the SDO fire detector defined in [figure 69](#) and shown as second member in the triples of [figures 17–46](#). The brighter patches mark brushfires ([section 7](#)) that are also seen better in the next images. Blinking back to the preceding reversed H α image in [figure 11](#) shows rough but remarkable overall pattern correspondences everywhere for the grainy grey chromosphere patches. This similarity is discussed in [appendix B](#).

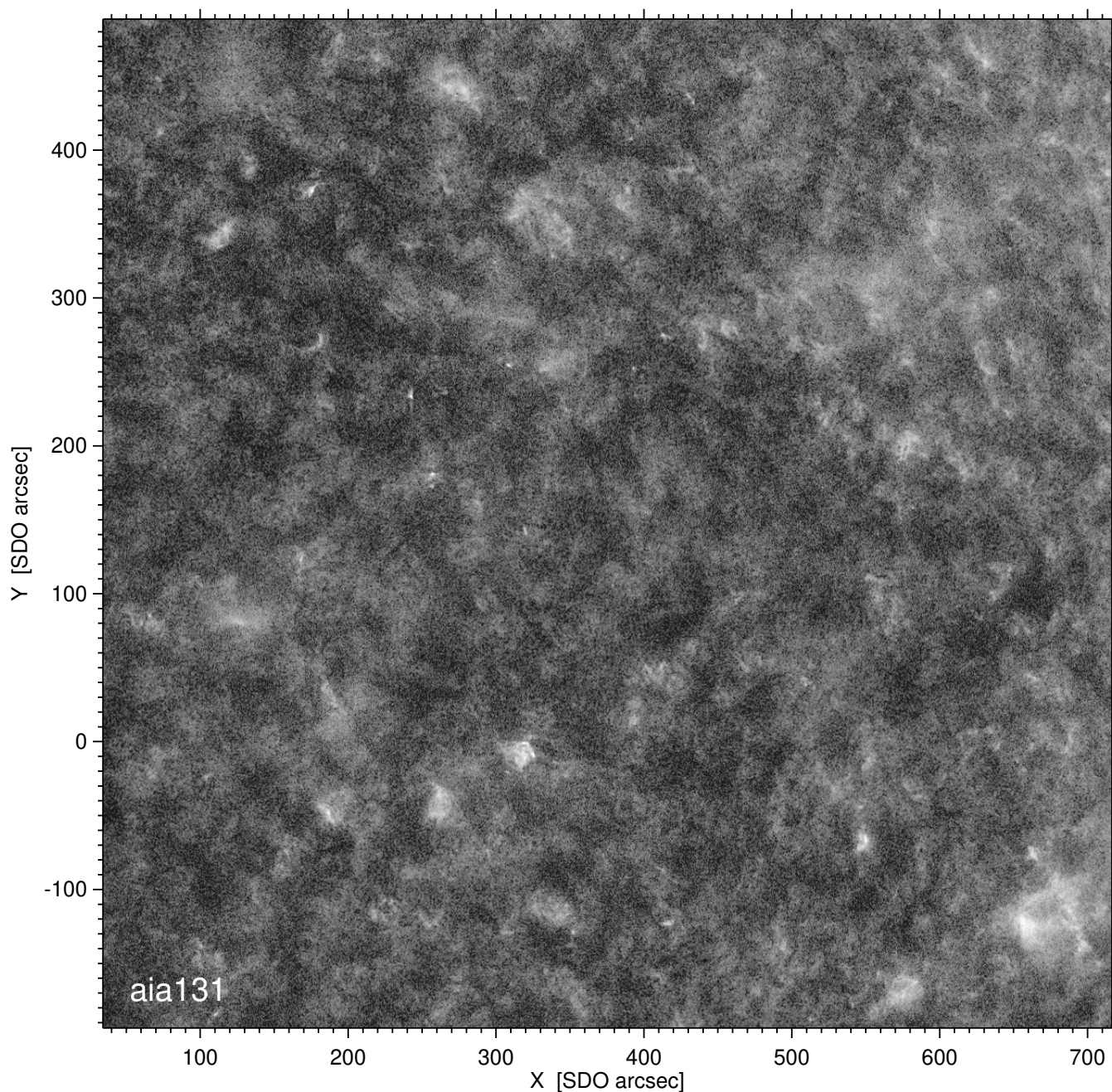


Fig. 13. The SDO field at best-match time in the AIA 131 Å image. The greyscale shows the logarithm of the intensity in rescaling with [sdo_intscale.pro](#) and clipping the brightest pixels in the 15-min sequence. This image is also noisy because the scene is so quiet, but it shows strict grey-patch correspondence with AIA 304 Å when blinking against preceding [figure 12](#), plus more diffuse brightenings that are clearer and more extended in the next AIA 171 Å image. Some campfires already stand out as tiny bright features. In [figure 69](#) this image is multiplied with the preceding 304 Å image to demonstrate feasibility of global SDO fire detection.

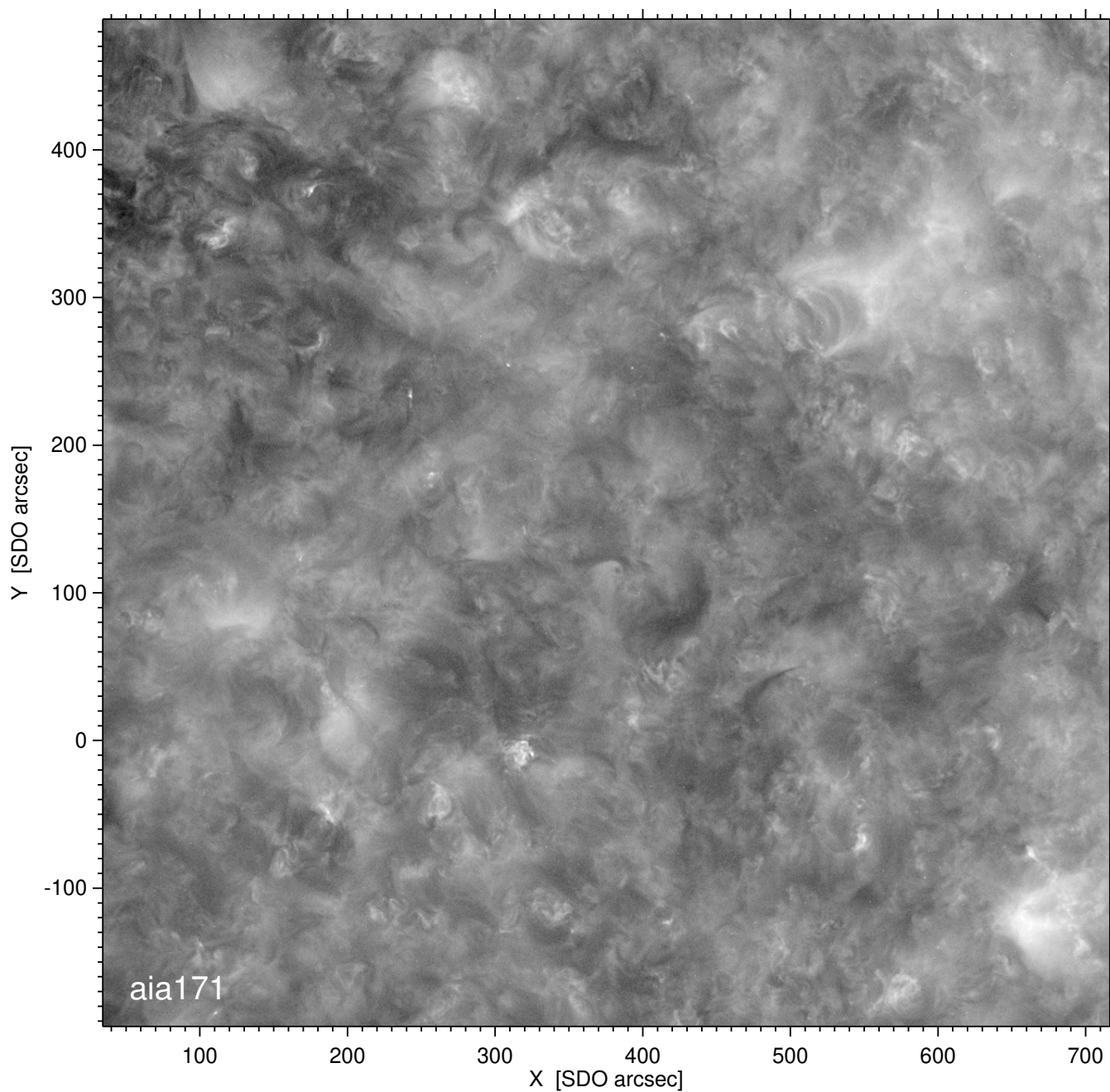


Fig. 14. The SDO field at best-match time in the AIA 171 Å image. The greyscale shows the logarithm of the intensity in rescaling with [sdo_intscale.pro](#) and clipping the brightest pixels in the 15-min sequence. Blinking against the 131 Å scene in [figure 13](#) shows addition of diffuse coronal connections. I expected this image to be the one to be compared to the SoHO press-release 174 Å image in [figure 1](#). They cannot be blinked directly because they differ much in foreshortening, but the target scene is indeed the same. Actually the next one suits better.

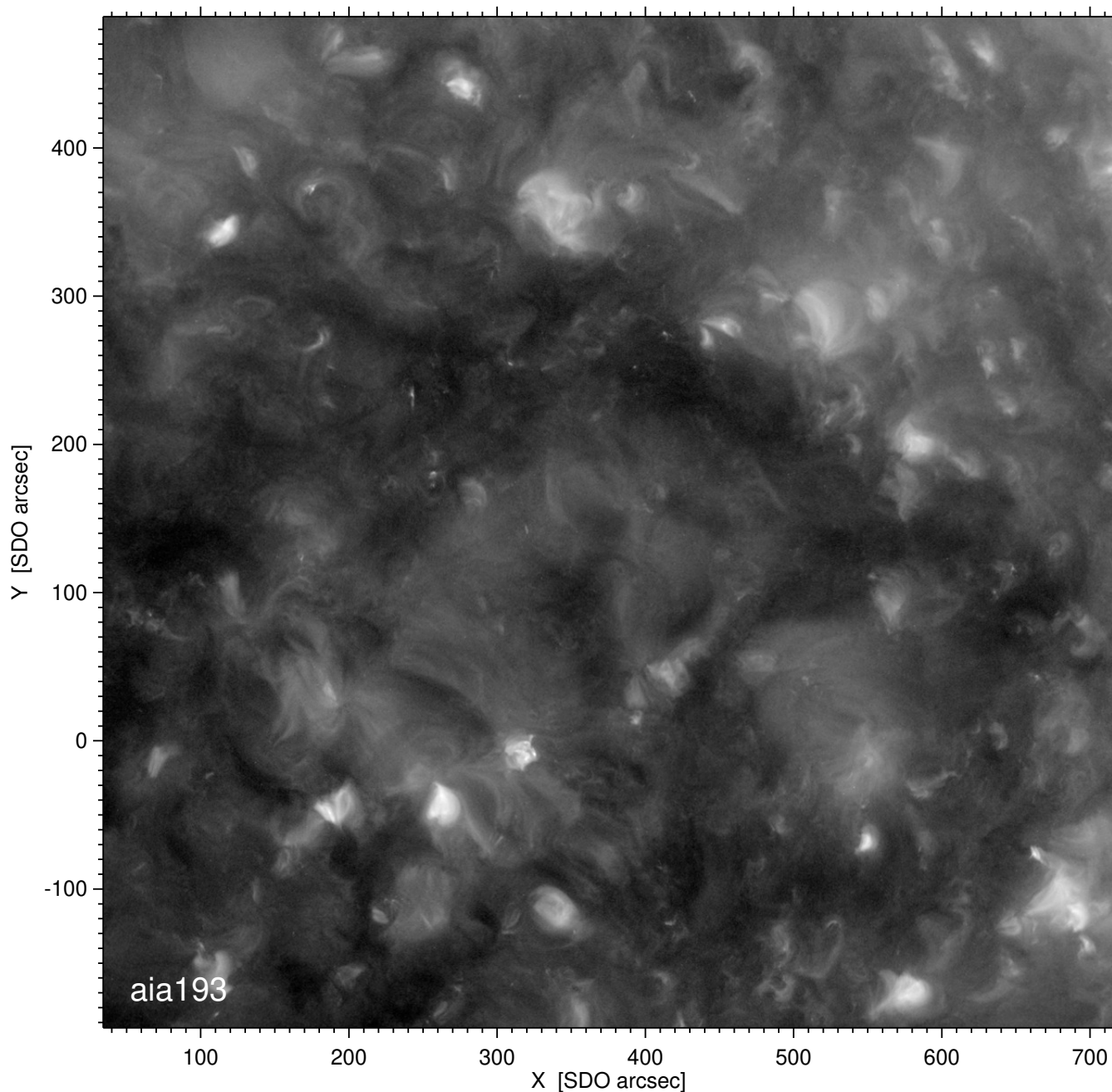


Fig. 15. The SDO field at best-match time in the AIA 193 Å image. The greyscale shows the logarithm of the intensity in rescaling with [sdo_intscale.pro](#) and clipping the brightest pixels in the 15-min sequence. It shows yet more hazy coronal connectivity than the 171 Å image in preceding [figure 14](#). The tiny campfires stand out brightly where they occur in dark areas. This image shows the best correspondence with the input press-release scene in [figure 1](#), perhaps through the common high-intensity tails in next [figure 16](#). The larger bright patches are treated as brushfires in [section 7](#). They represent classical coronal bright points (review by [Madjarska 2019](#)). They are smaller and more homogeneously bright than in 171 and 131 Å where they partly contain darker fibrils between brighter feet.

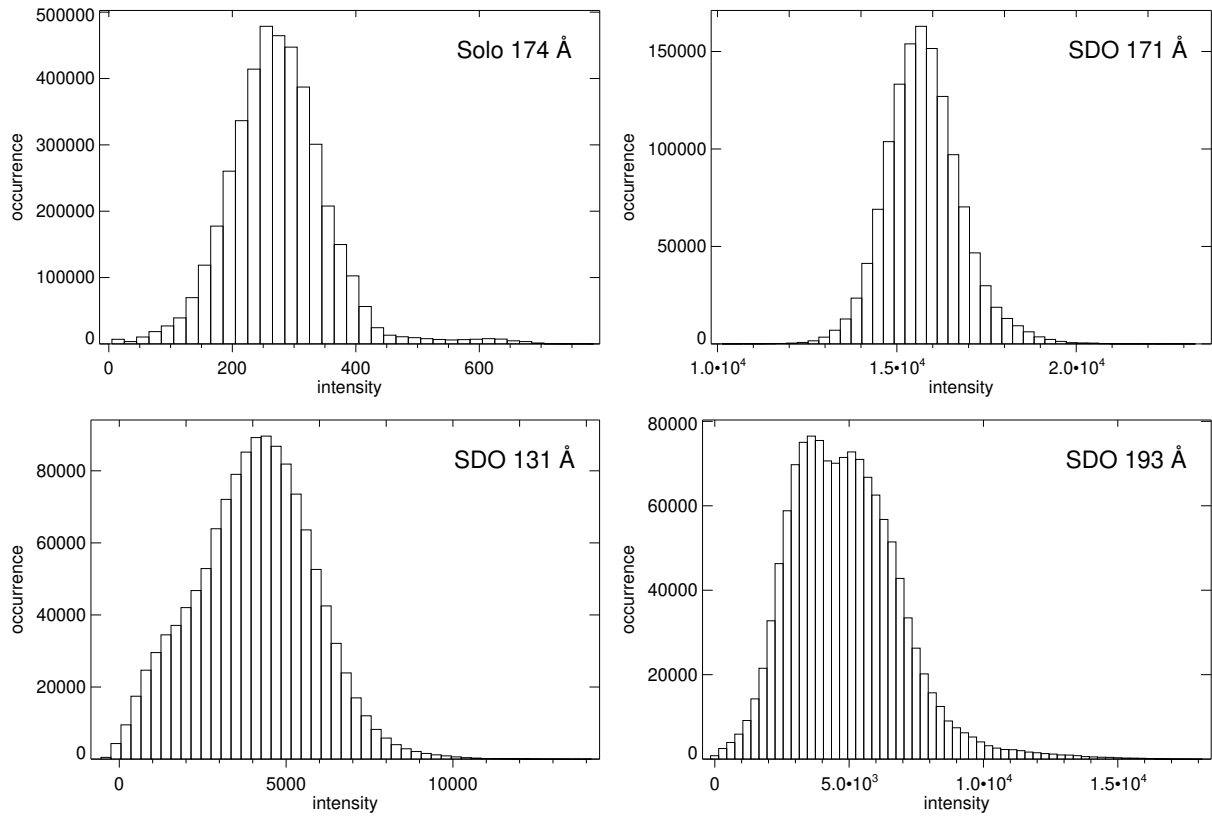


Fig. 16. Histograms of the pixel intensities in the Solo 174 Å image and in three SDO images at the best-match time, respectively SDO 171 Å, 131 Å and 193 Å. Extended highest-brightness tails show up in all but especially in the Solo 174 Å and AIA 193 Å distributions. The latter also shows a double-hump peak; there are indeed many dark areas in [figure 15](#).

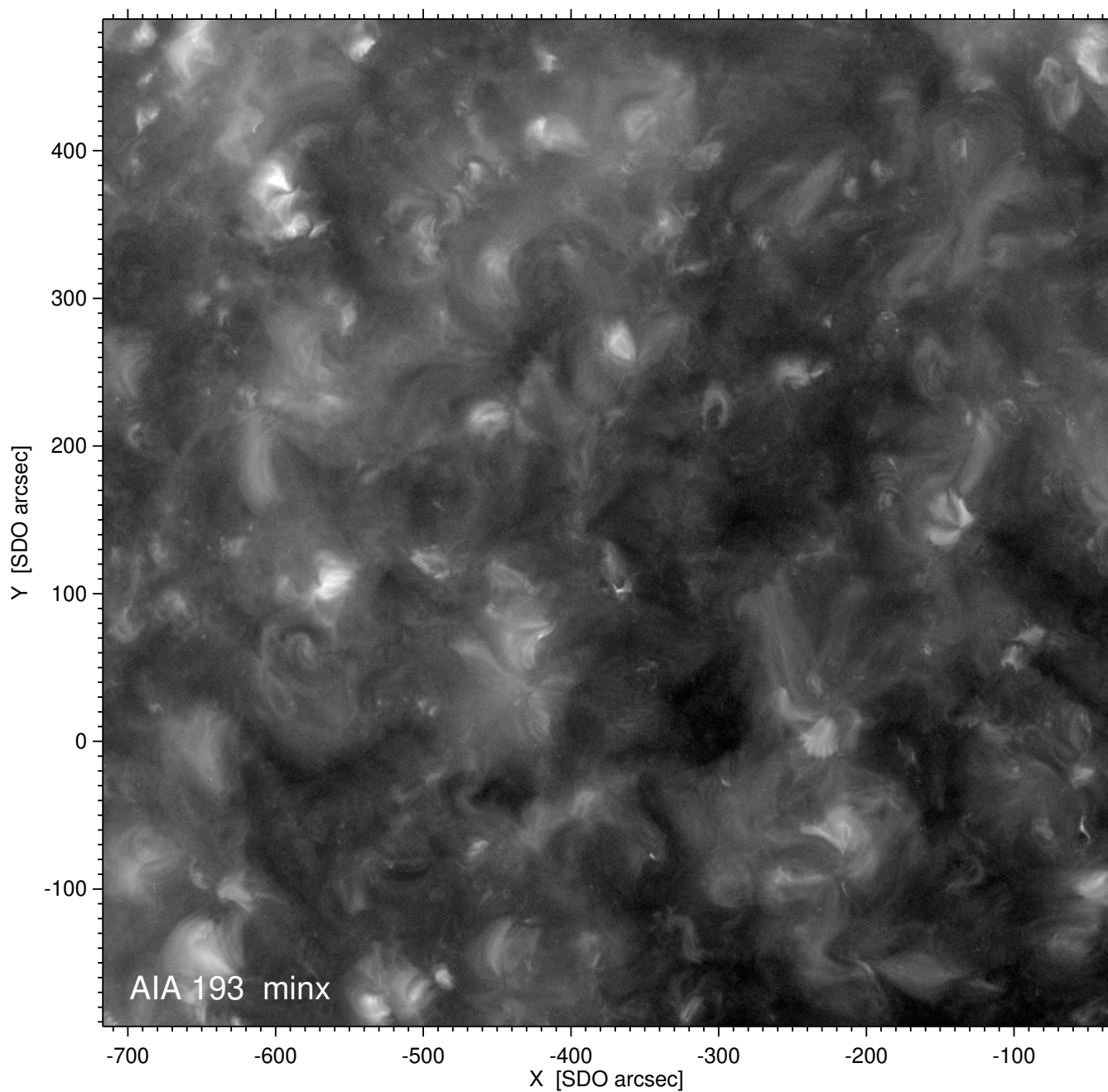


Fig. 17. Comparable AIA 193 Å cutout for May 30, 2020 14:58:46 UT as in [figure 15](#) but East at $(X, Y) = (-375, 148)$. Just as the SolO field this same-size other field shows about a dozen tiny campfires and more larger brushfires. Wider-connecting diffuse 193 Å brightness patterns occur mostly around brushfires and suggest origin in earlier or persistent brushfires.

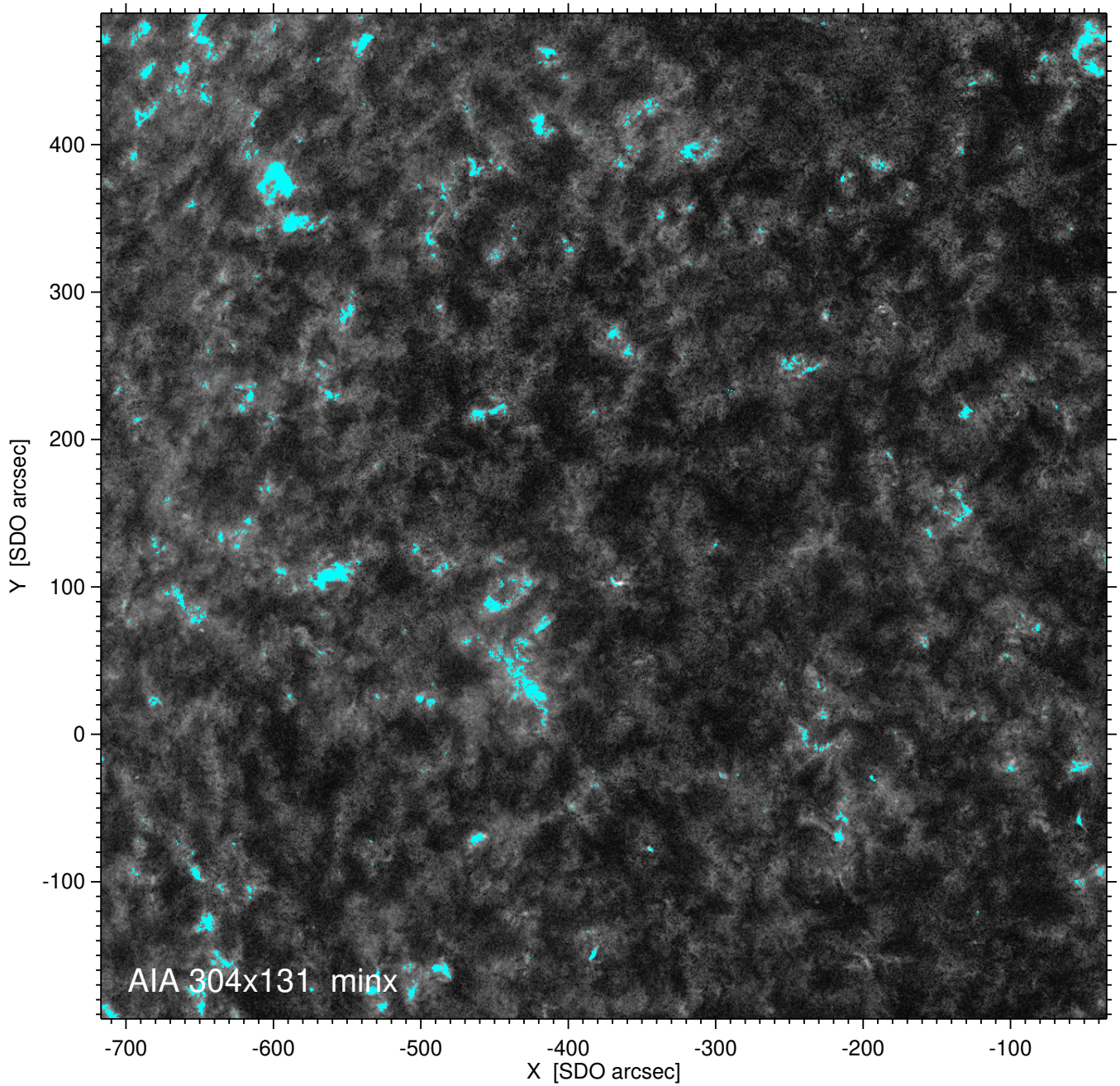


Fig. 18. SDO fire detector cutout for the same field as in preceding [figure 17](#). Its construction is described in the caption of [figure 69](#). It serves to separate chromospheric heating (ubiquitous grey patches) and coronal heating (small dispersed areas colored cyan). In these and the following “other SDO scene” triples these fire detector images are inserted between the AIA 193 Å images and the HMI magnetograms for blinking backward and forward with these. It shows that many small bright 193 Å loop bundles constituting larger brushfires have cyan-colored detector brightenings at their feet located in bipolar network. The smallest point-like campfires go without such closed-loop connectivity.

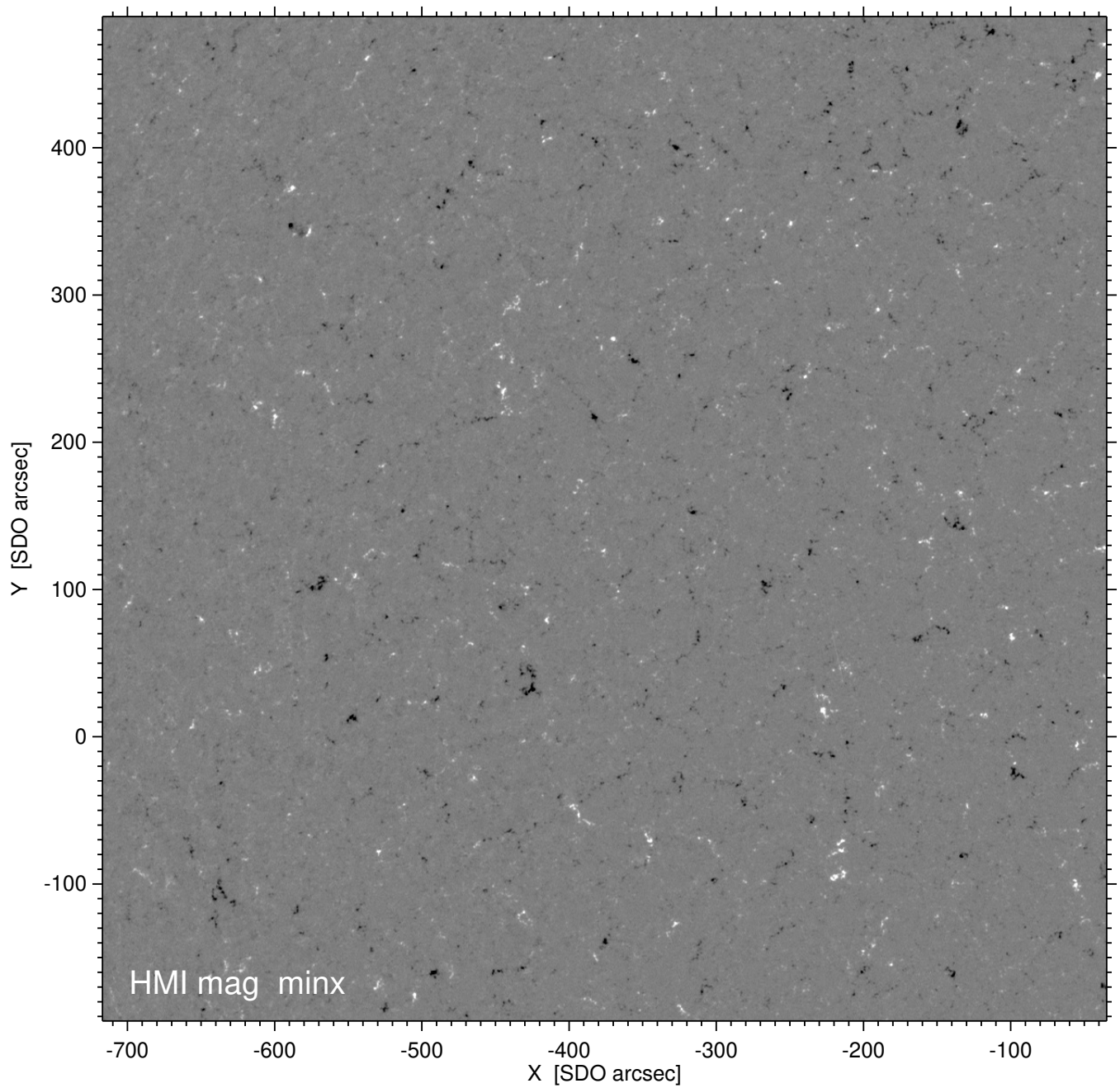


Fig. 19. HMI magnetogram for the field in the two preceding figures. The field strengths are clipped as described for [figure 7](#). Blinking with the two preceding figures shows that small “brushfire” loop bundles in 193 \AA connect small groups of opposite-polarity MCs.

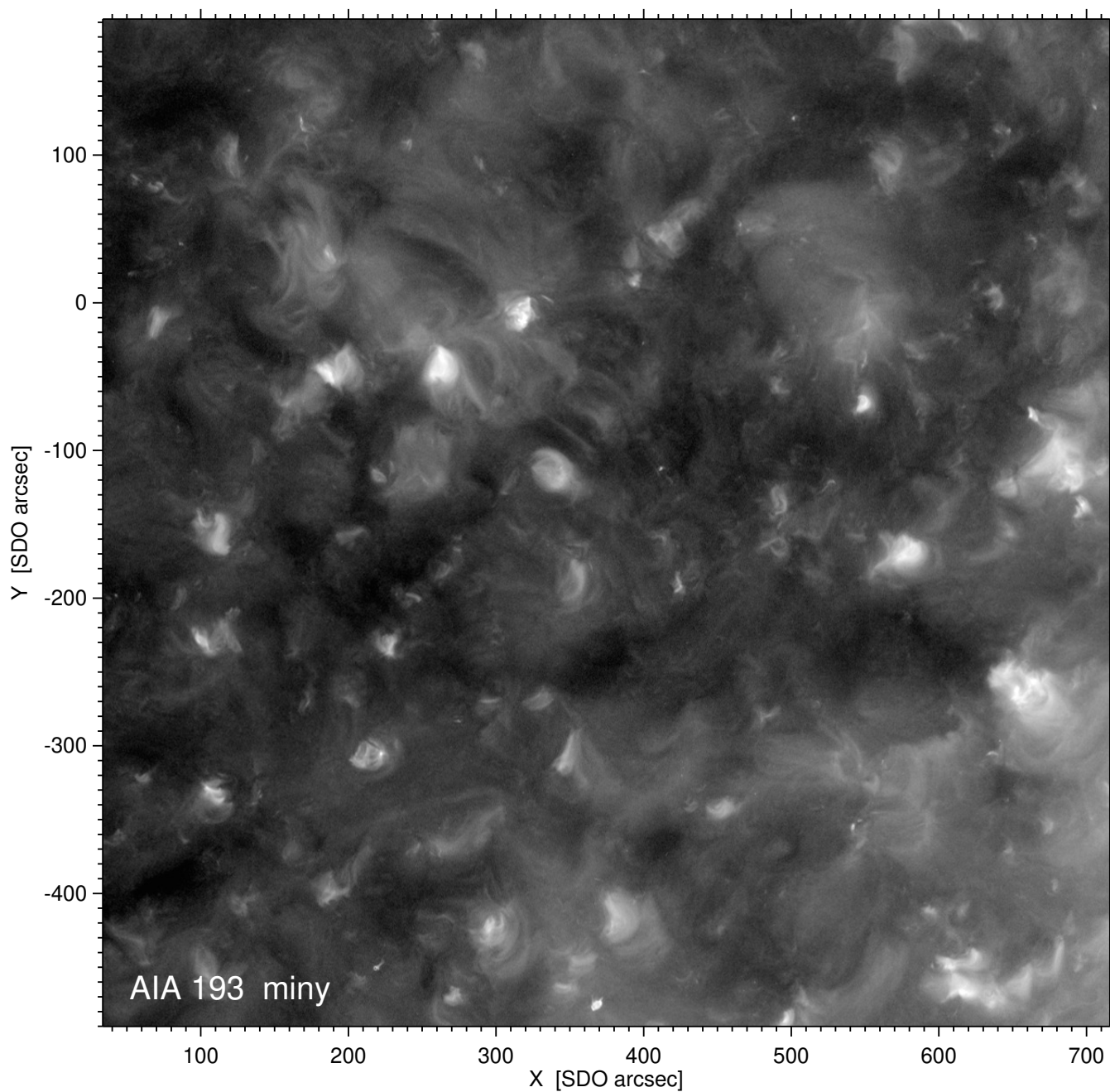


Fig. 20. Comparable AIA 193 Å cutout for May 30, 2020 14:58:46 UT T as in [figure 15](#) but South at $(X, Y) = (375, -148)$. Again about a dozen tiny campfires and more larger brushfires.

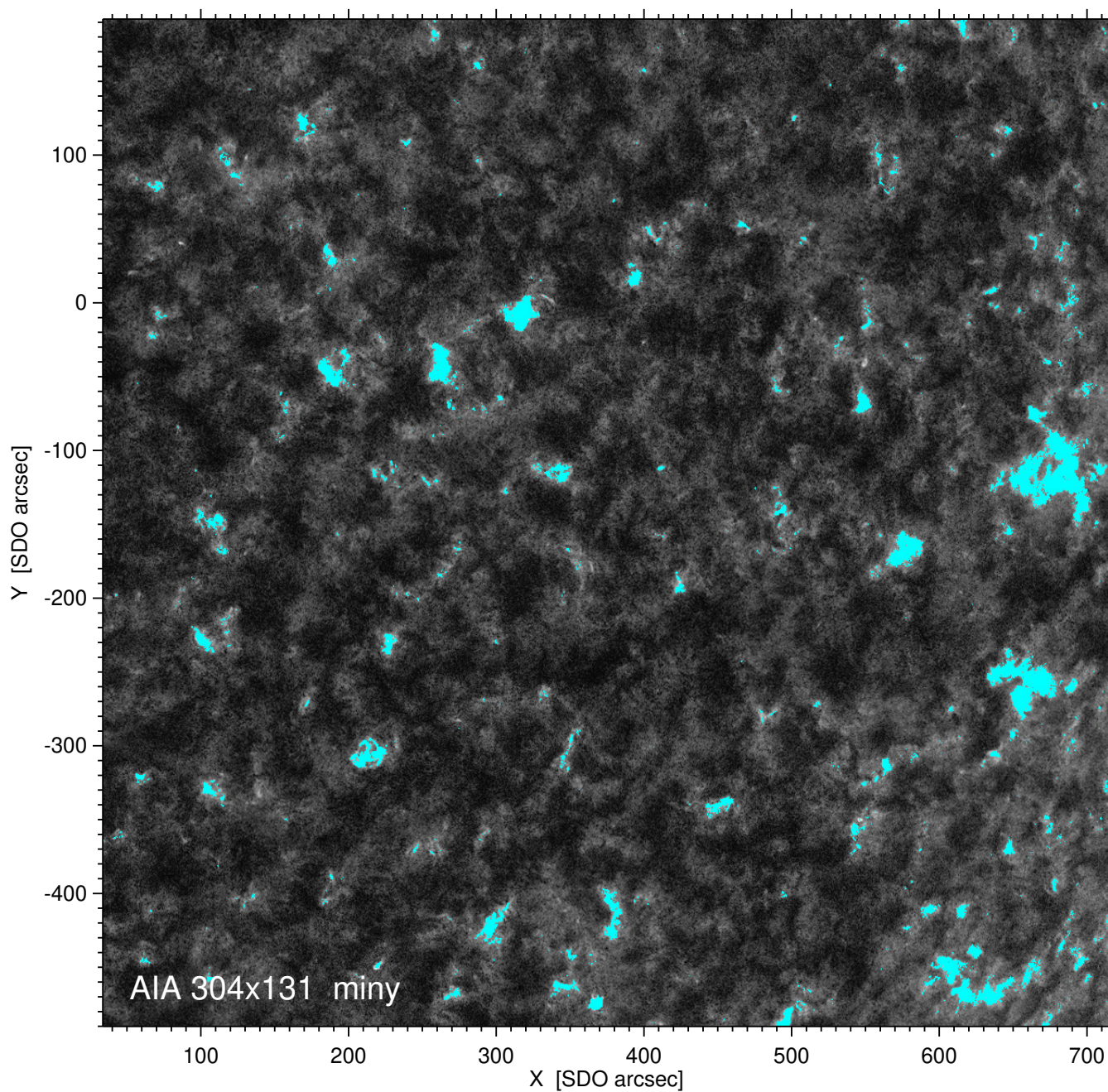


Fig. 21. SDO fire detector cutout for the same field as in preceding [figure 20](#).

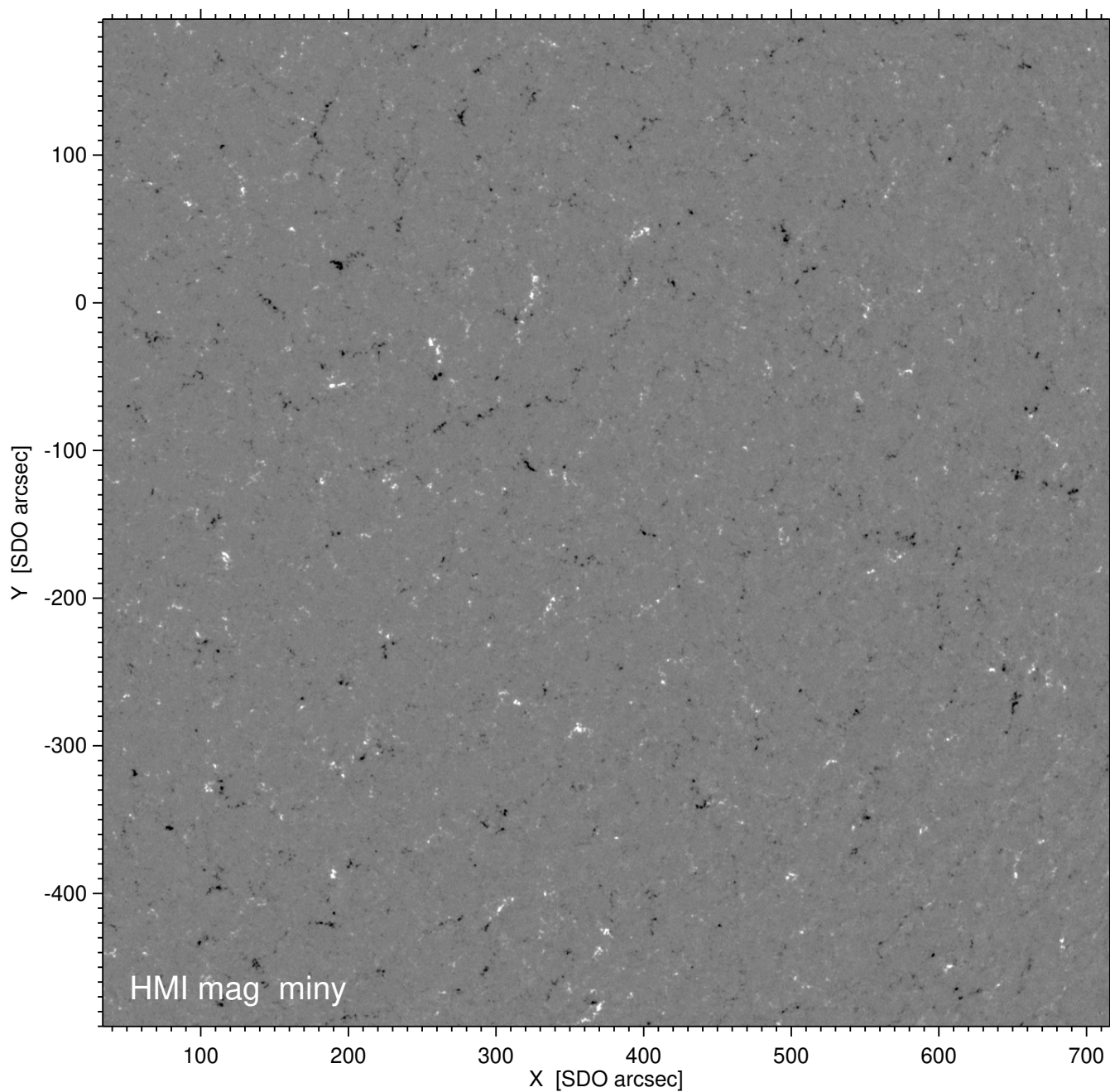


Fig. 22. HMI magnetogram for the field in the two preceding figures.

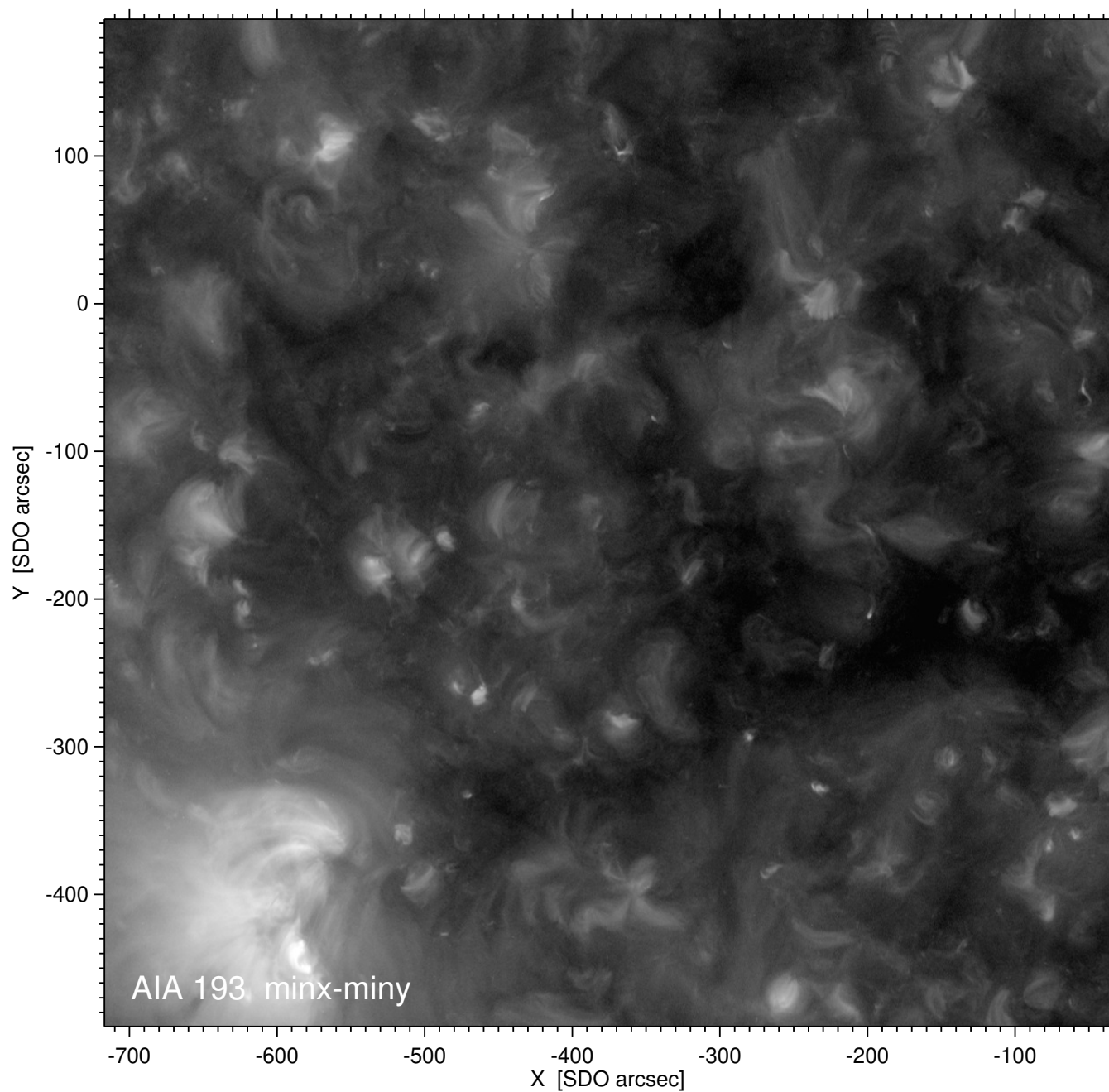


Fig. 23. Comparable AIA 193 Å cutout for May 30, 2020 14:58:46 UT as in [figure 15](#) but South-East at $(X, Y) = (-375, -148)$.

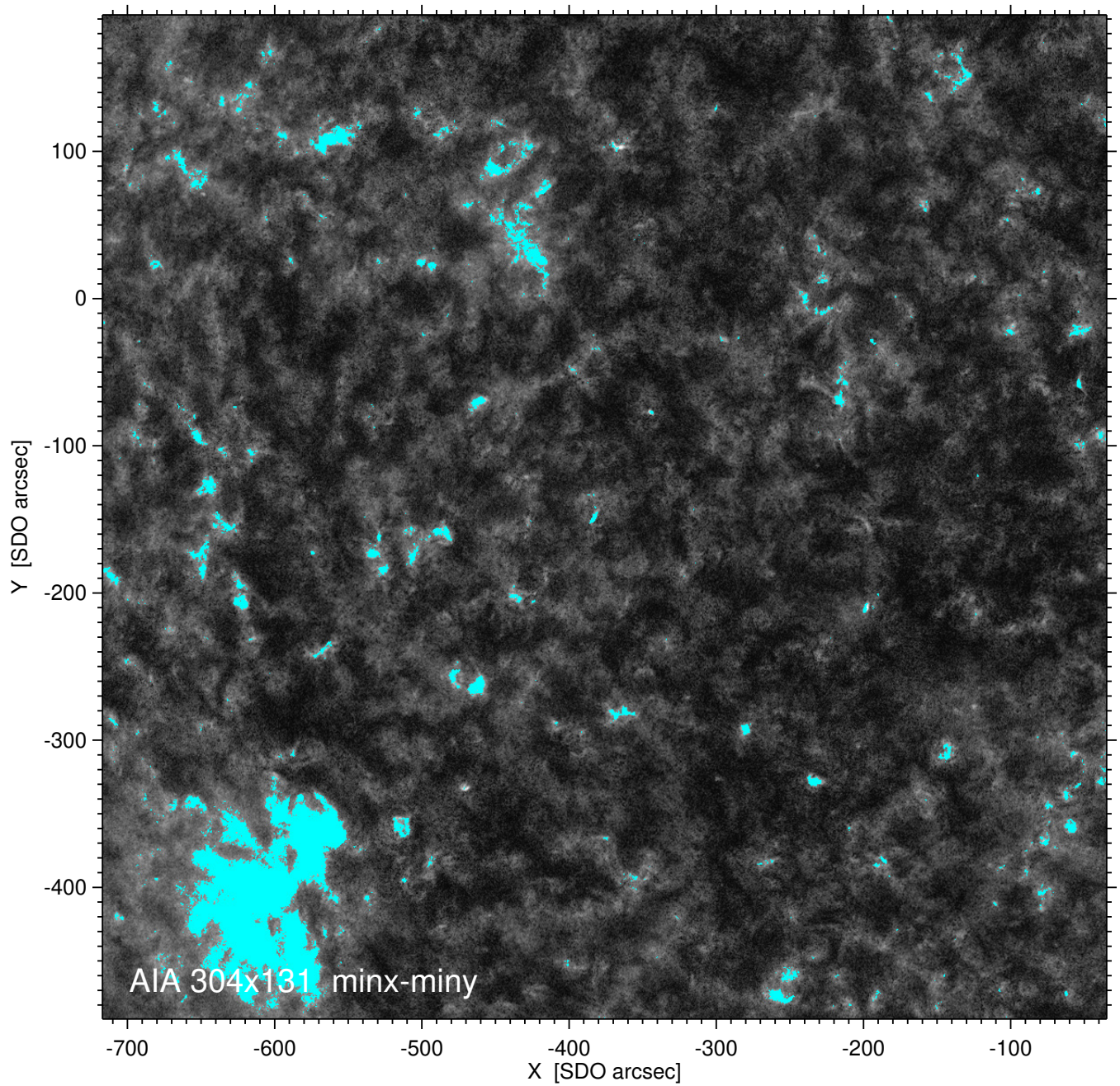


Fig. 24. SDO fire detector cutout for the same field as in the preceding figure. Around the small active plage at lower-left some campfires are veiled by coronal loops in the preceding AIA 193 Å image but appear unveiled in this chart.

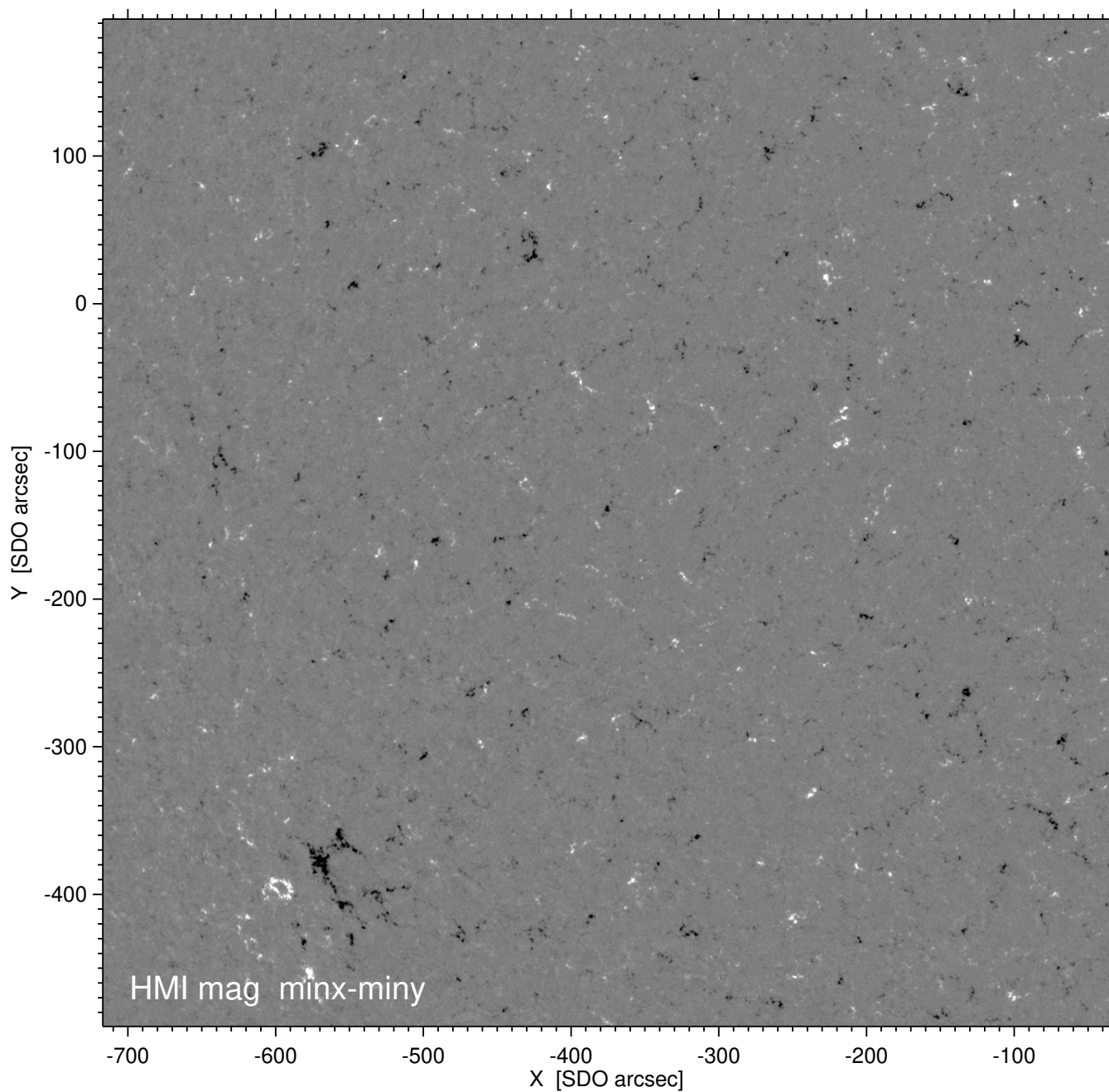


Fig. 25. HMI magnetogram for the field in the two preceding figures.

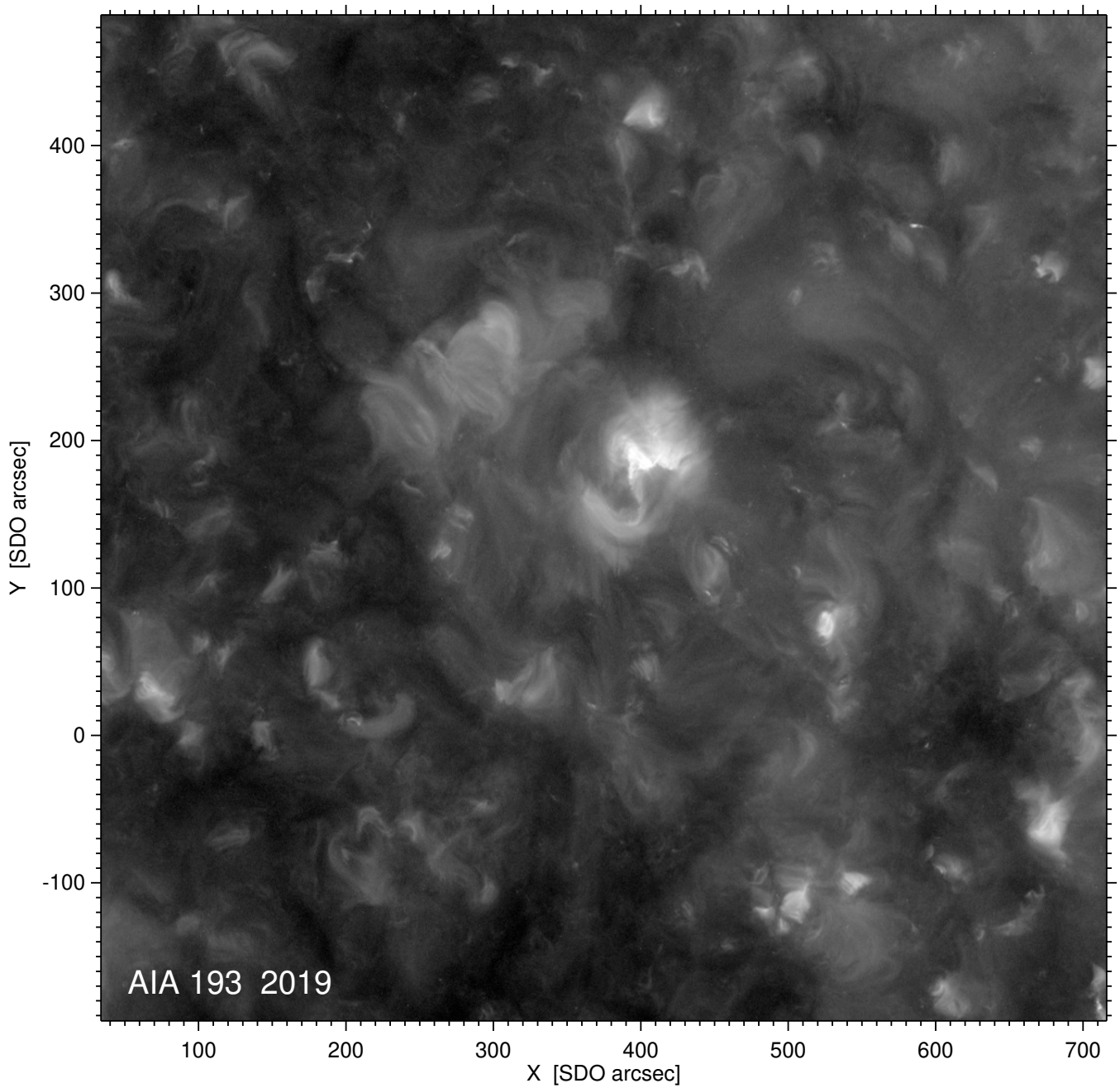


Fig. 26. Comparable AIA 193 Å cutout for the same $(X, Y) = (375, 148)$ arcsec location as best-match [figure 15](#) and also on May 30 near 14:58 UT, but in 2019. There is a small active plage near the center.

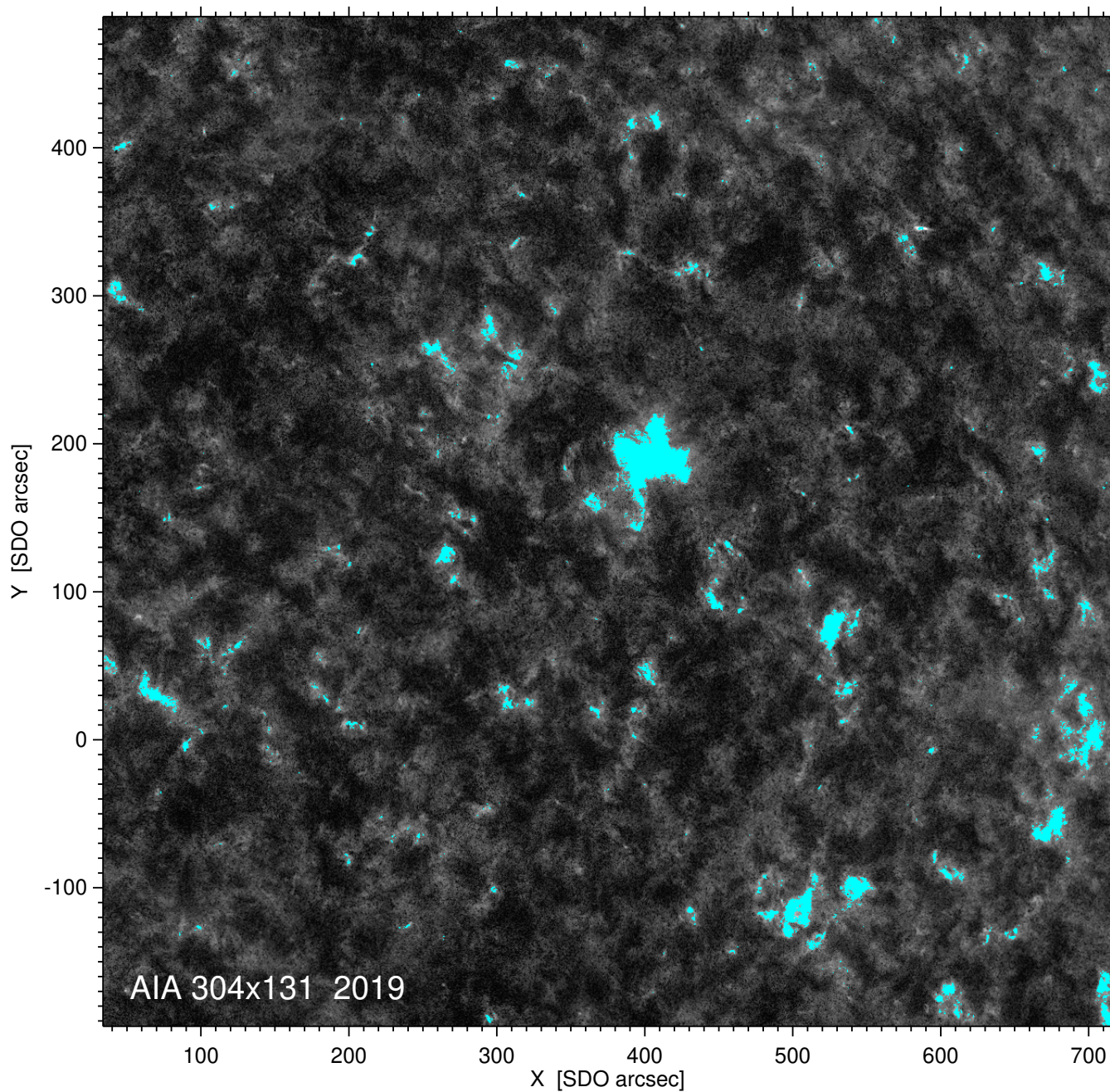


Fig. 27. SDO fire detector cutout for the same field as in the preceding figure.

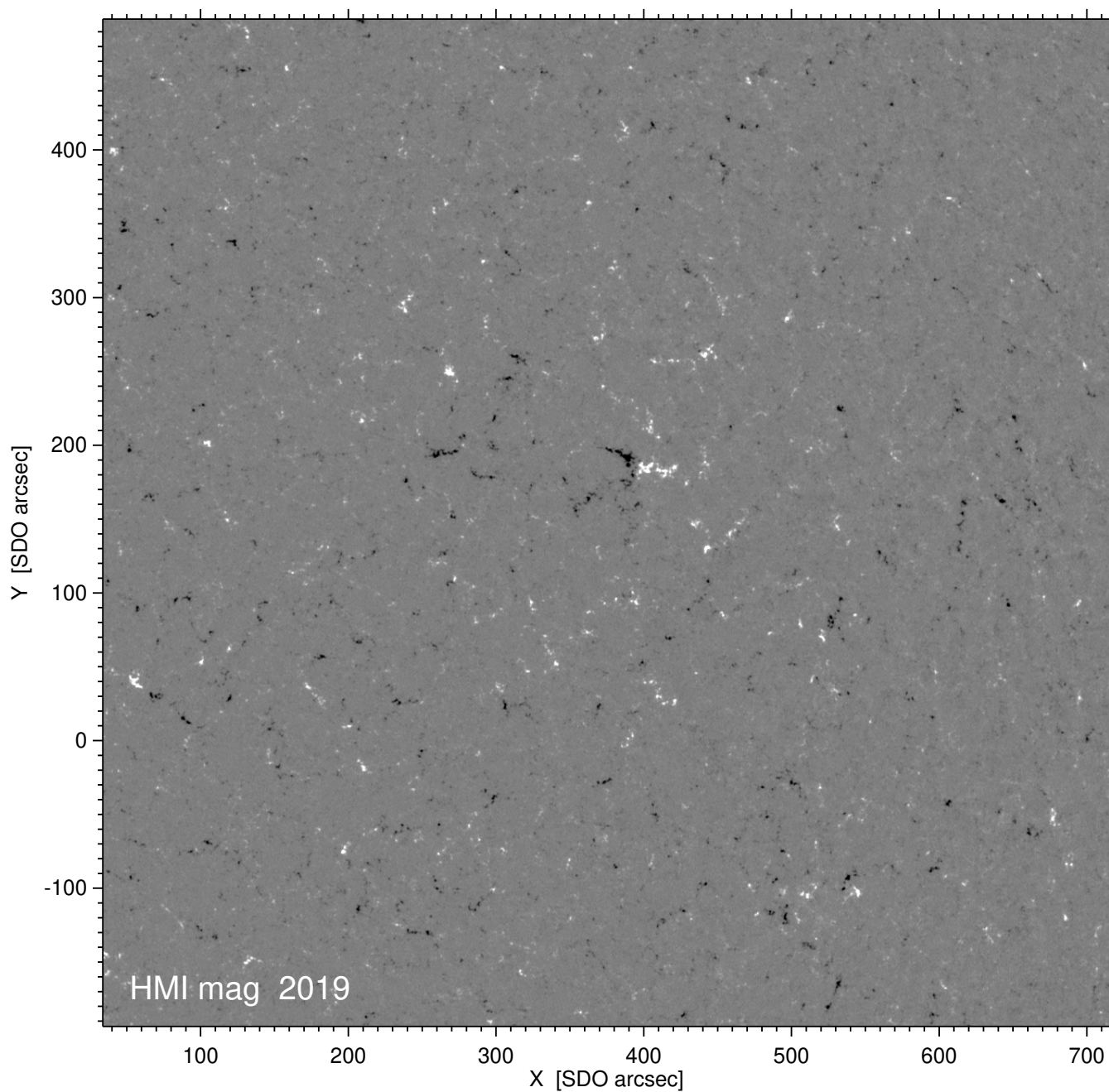


Fig. 28. HMI magnetogram for the field in the two preceding figures.

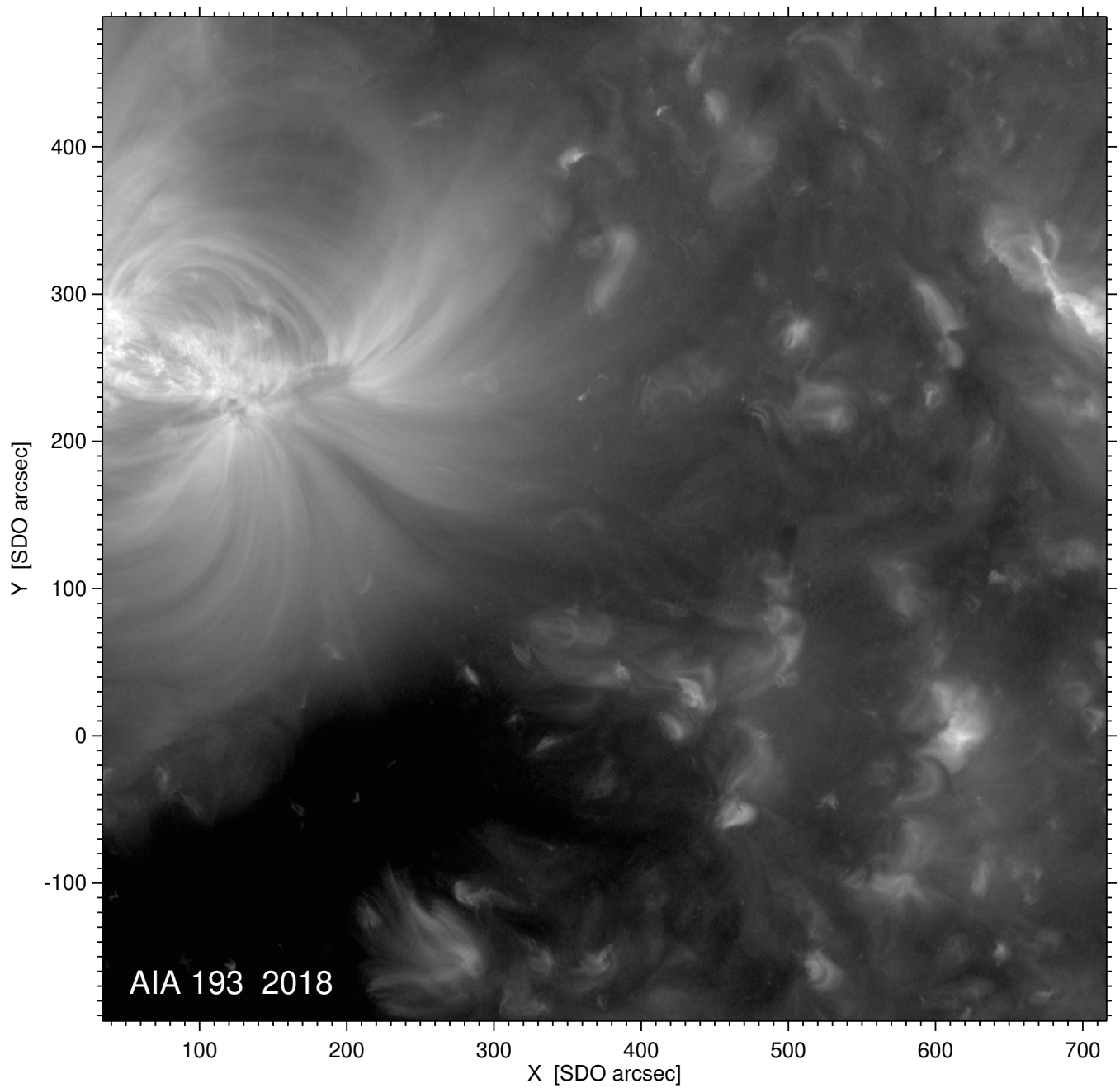


Fig. 29. Comparable AIA 193 Å cutout for the same $(X, Y) = (375, 148)$ arcsec location as best-match [figure 15](#) and also on May 30 near 14:58 UT, but in 2018. This scene is the most active portrayed in this report.

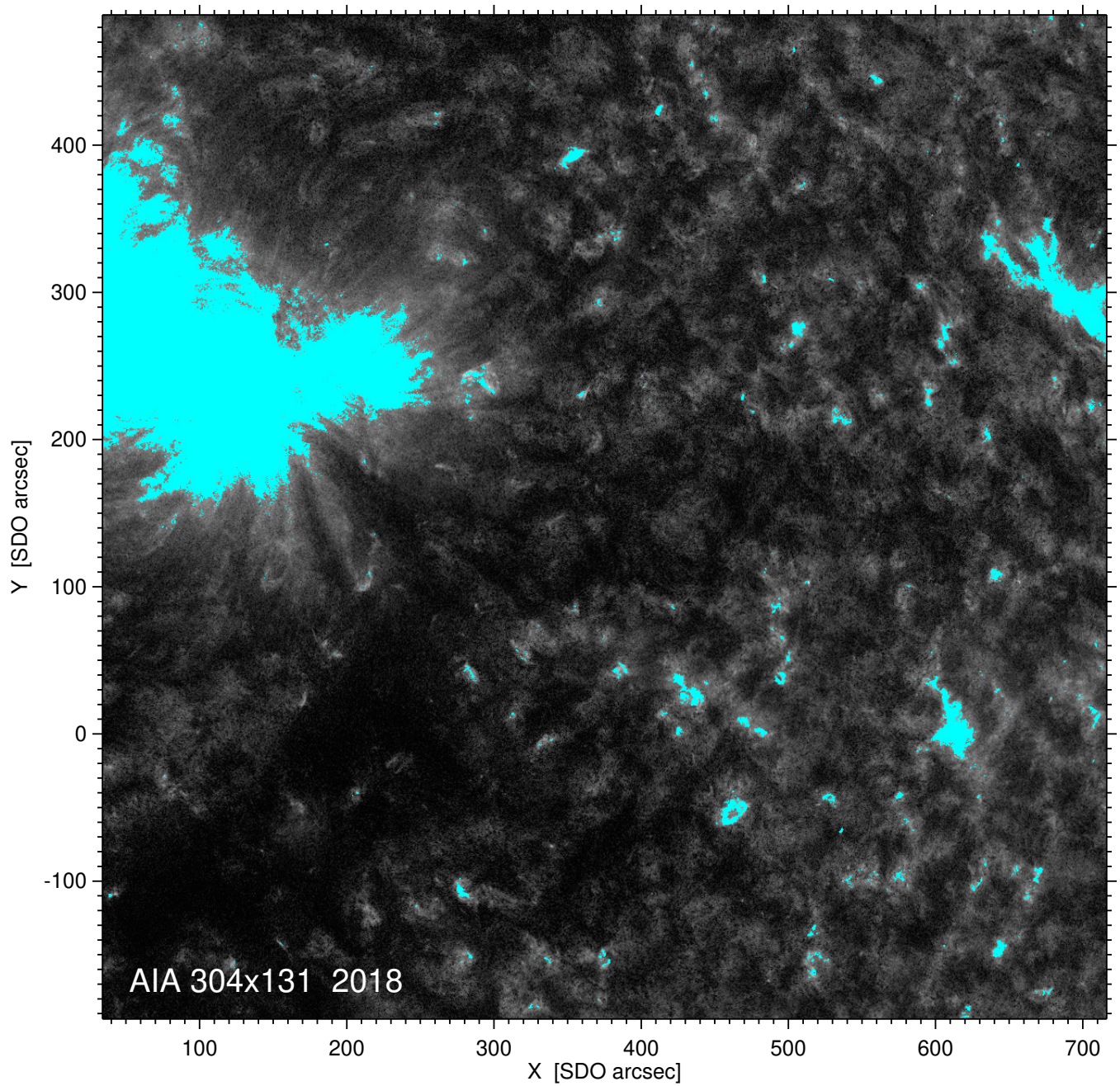


Fig. 30. SDO fire detector cutout for the same field as in the preceding figure. The bytescale is clipped for the active region to maintain visibility (grey) of the quiet network elsewhere, as described under [figure 69](#).

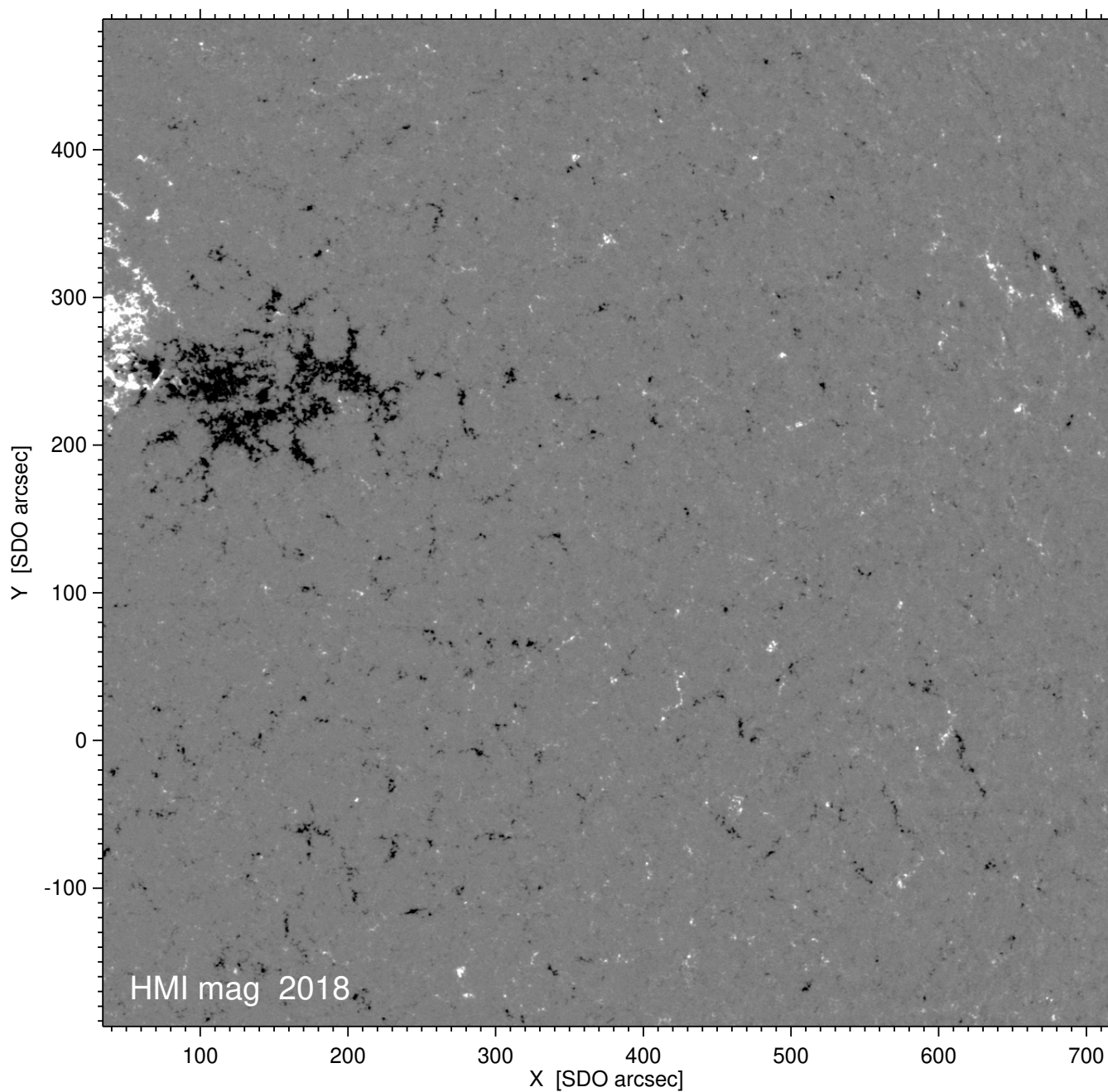


Fig. 31. HMI magnetogram for the field in the two preceding figures.

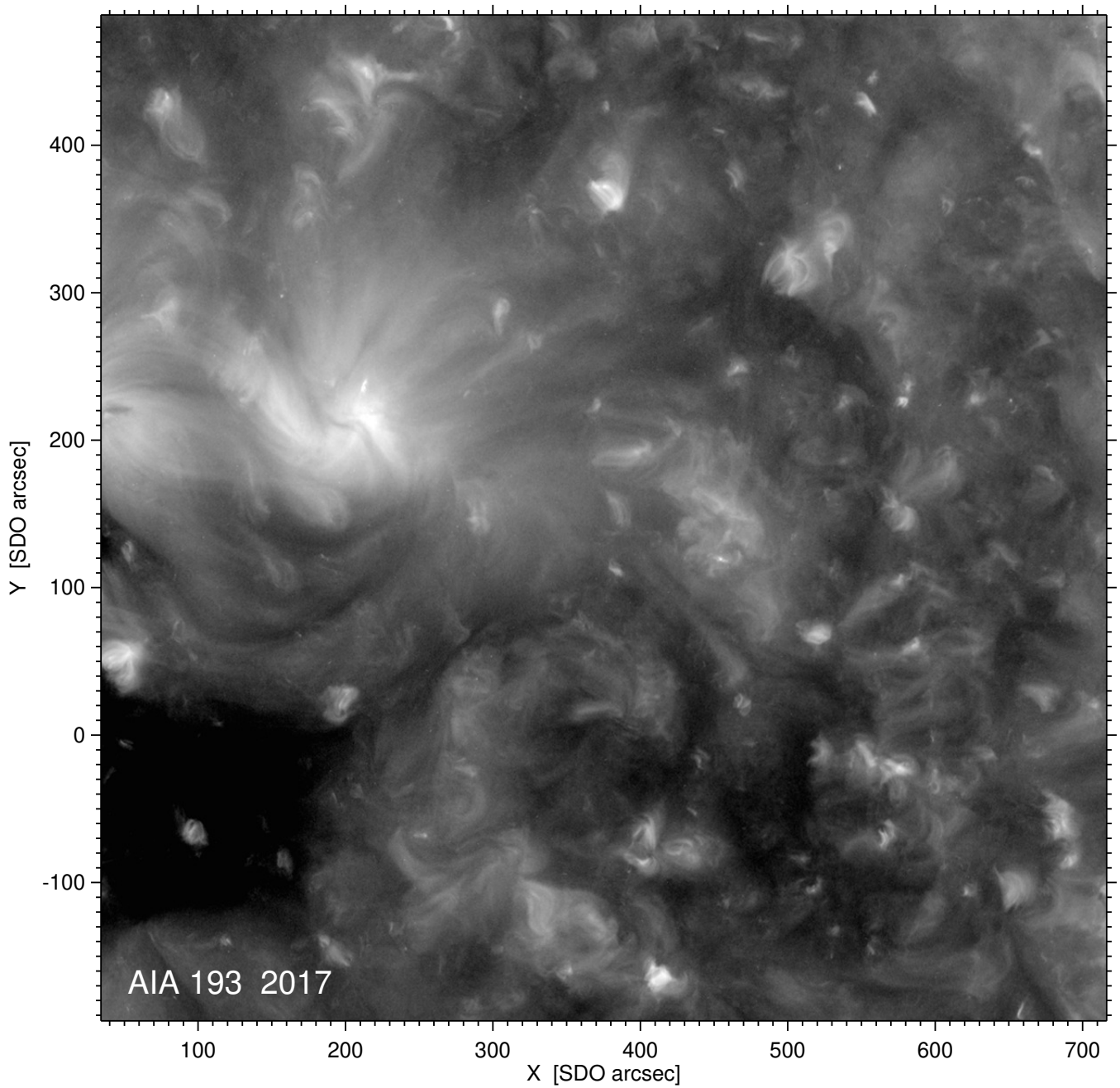


Fig. 32. Comparable AIA 193 Å cutout for the same $(X, Y) = (375, 148)$ arcsec location as best-match [figure 15](#) and also on May 30 near 14:58 UT, but in 2017.

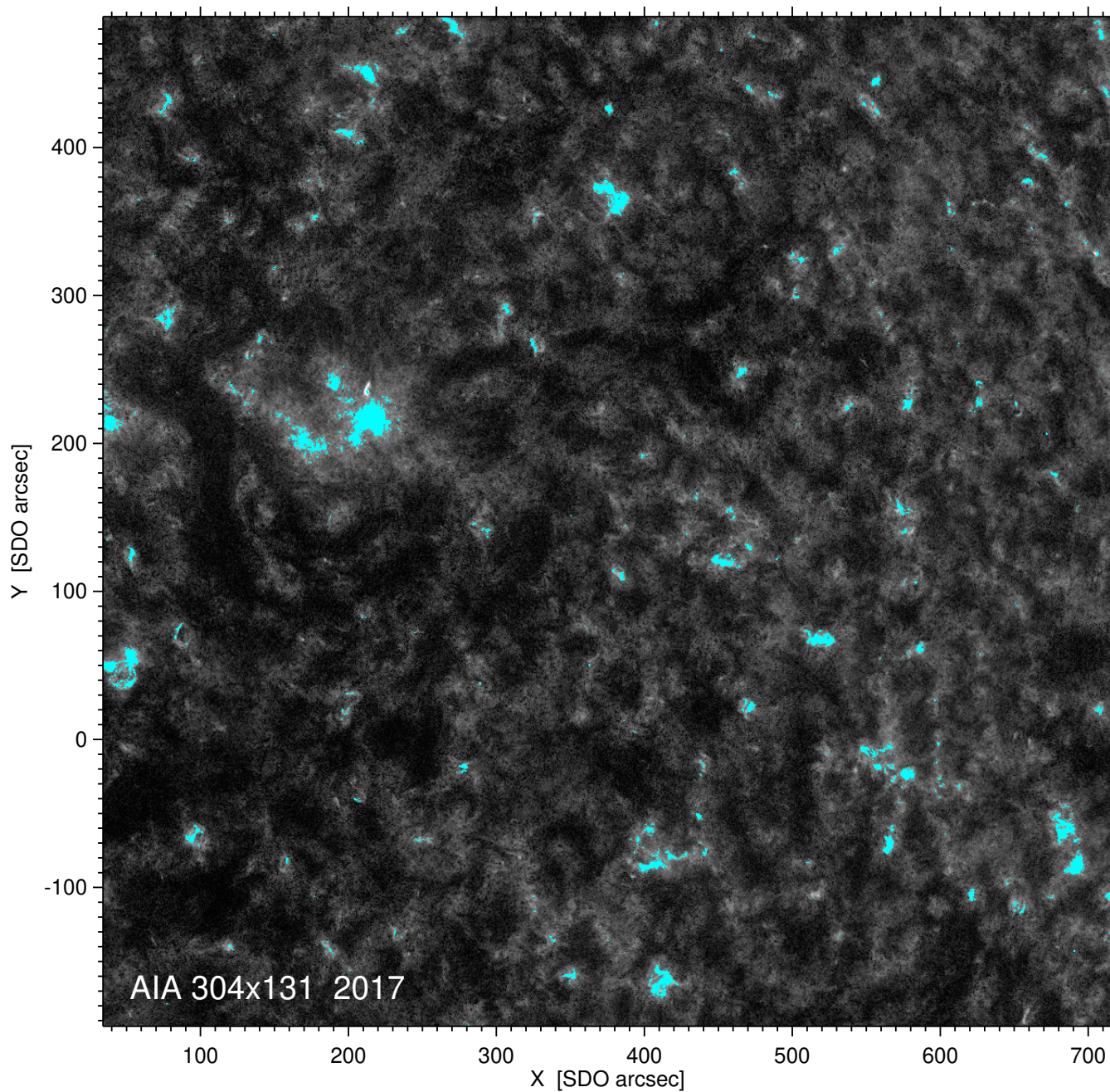


Fig. 33. SDO fire detector cutout for the same field as in the preceding figure.

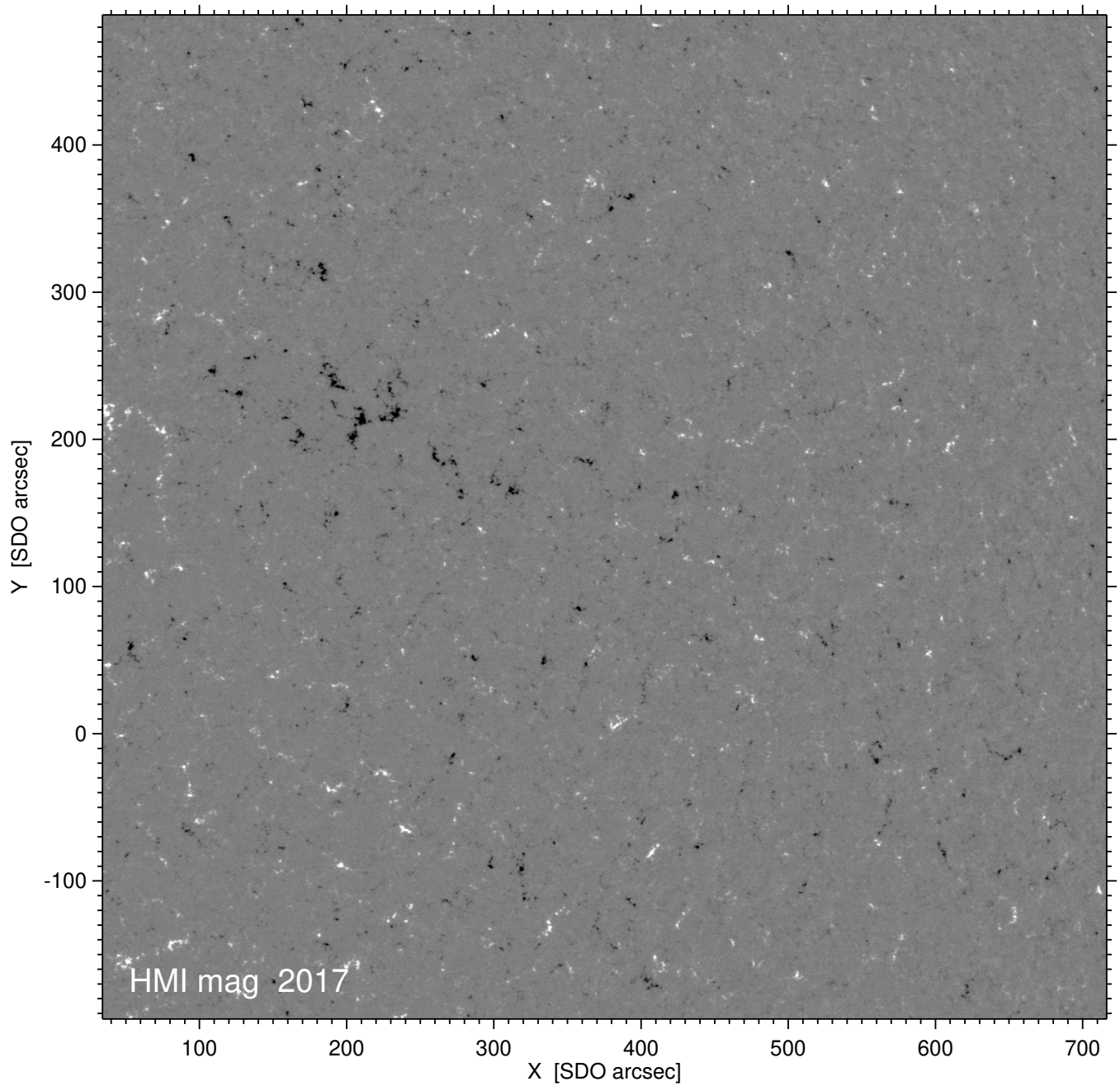


Fig. 34. HMI magnetogram for the field in the two preceding figures. The small active region is mostly monopolar but at higher sensitivity than offered by HMI it is rather likely that there are or have been canceling white-polarity MCs.

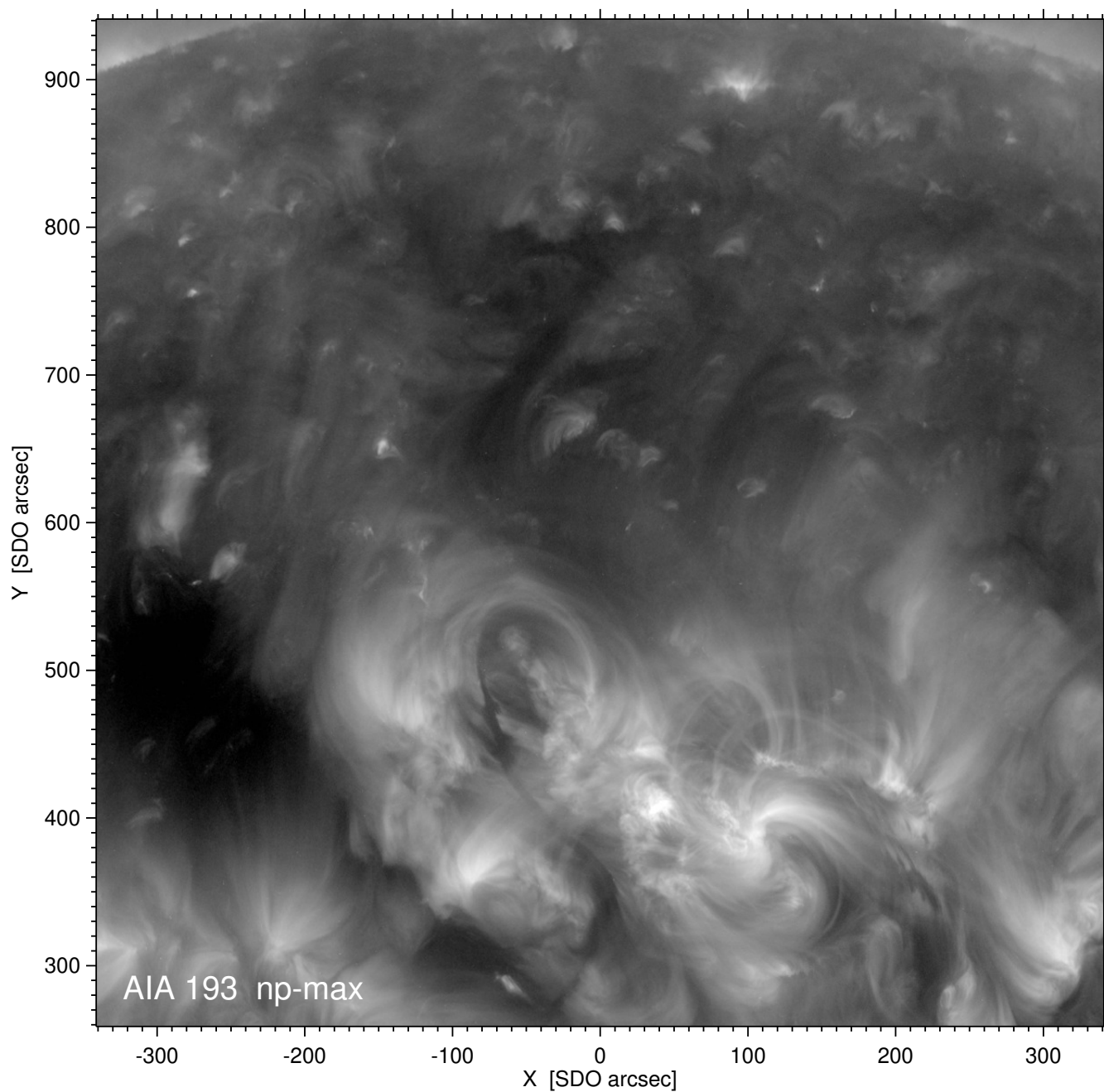


Fig. 35. AIA 193 Å cutout near the solar North pole on April 1, 2014 at 00:00 UT. Much activity at lower latitudes.

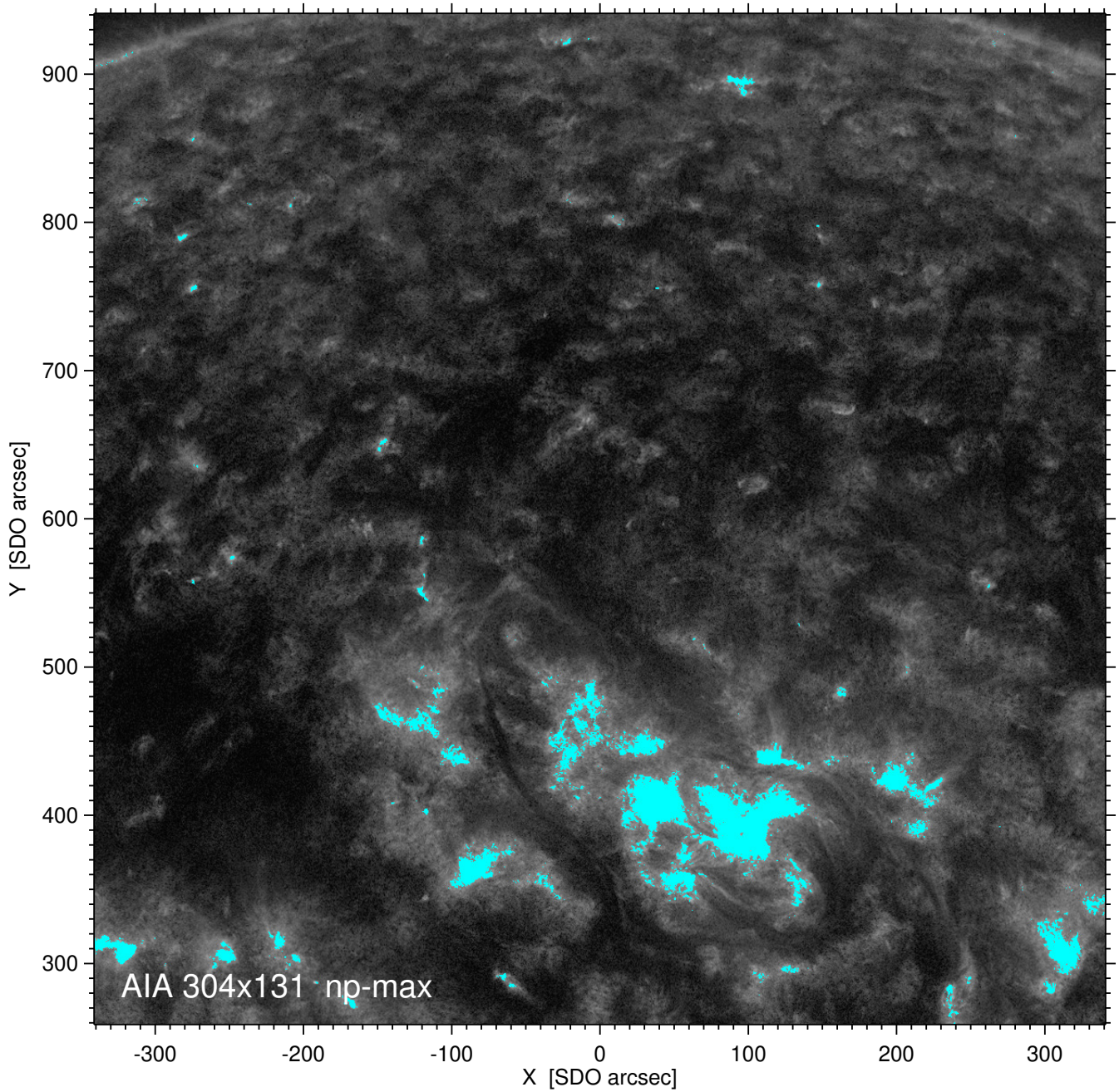


Fig. 36. SDO fire detector cutout for the same field as in the preceding figure. There are very few fires here in the upper part North of the active regions. All the grey chromosphere patches suggest more. I wonder whether you must look down their throat to see them. I applied `heightdiff = 1000 km` correction (see [appendix A](#)) to the whole field but this made no difference. There may also be too much veiling along the slanted lines of sight by all the widely-connected coronal haze in the preceding figure.

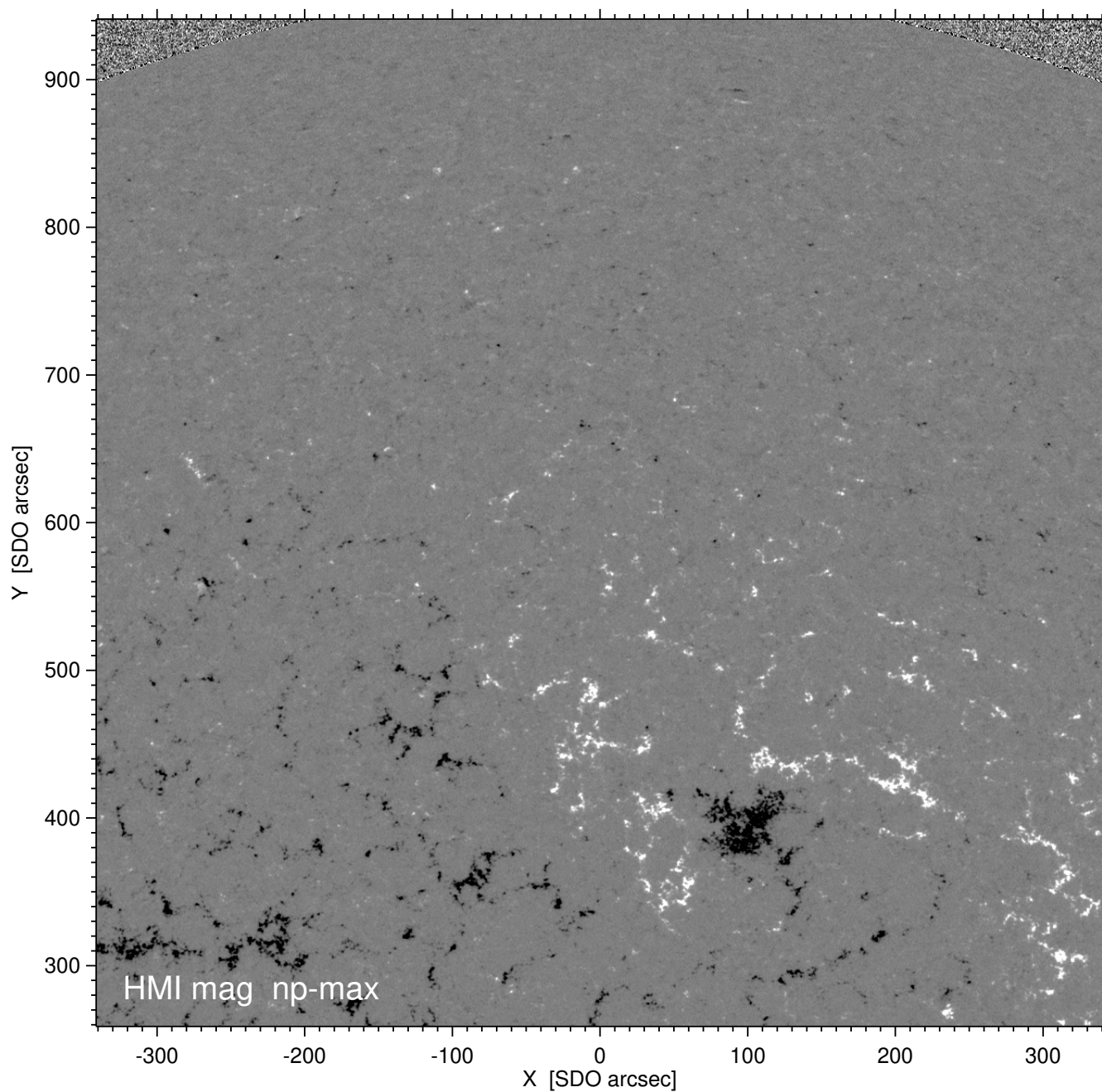


Fig. 37. HMI magnetogram for the field in the two preceding figures.

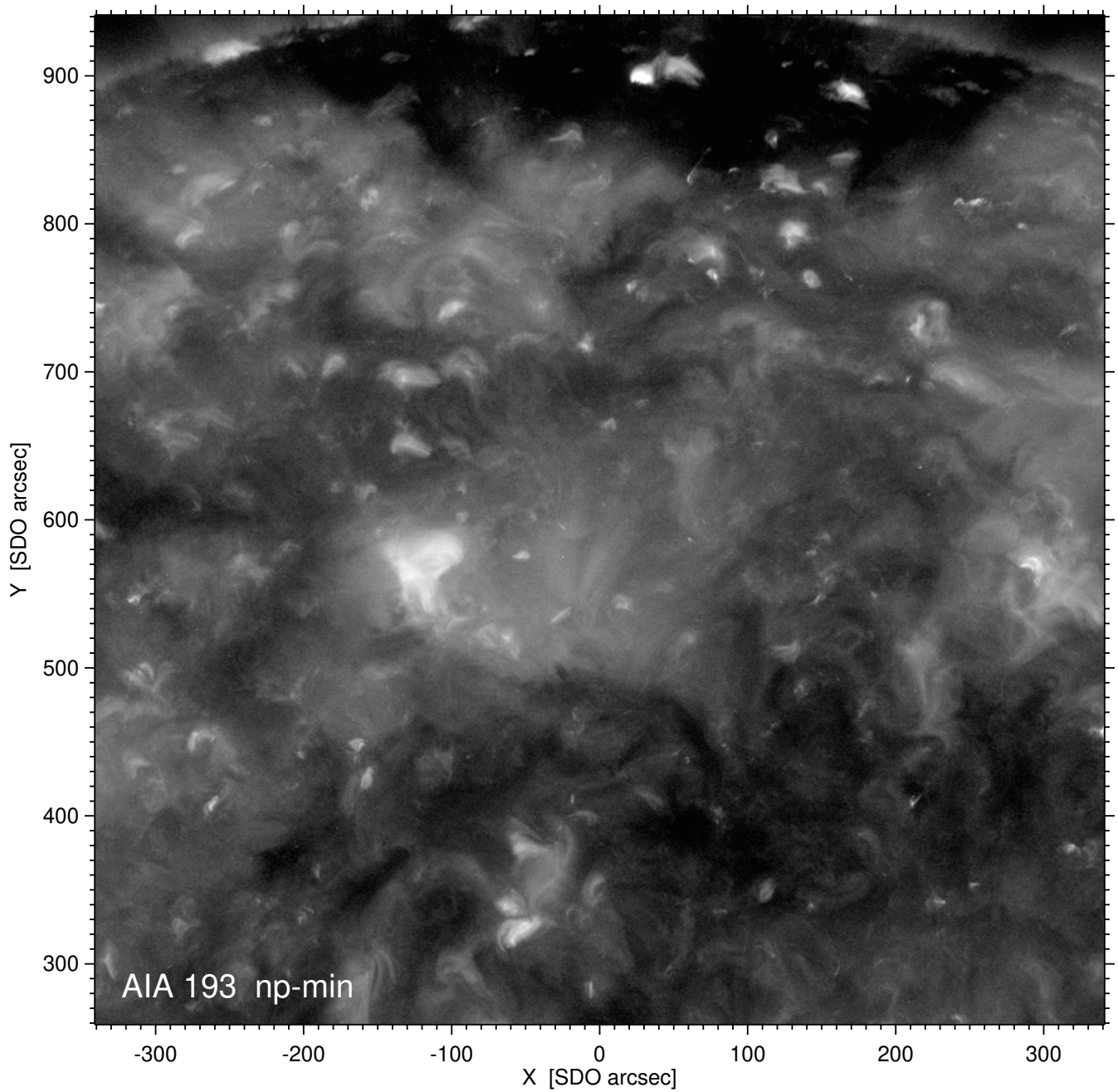


Fig. 38. AIA 193 Å cutout near the solar North pole on June 1, 2019 at 00:00 UT.

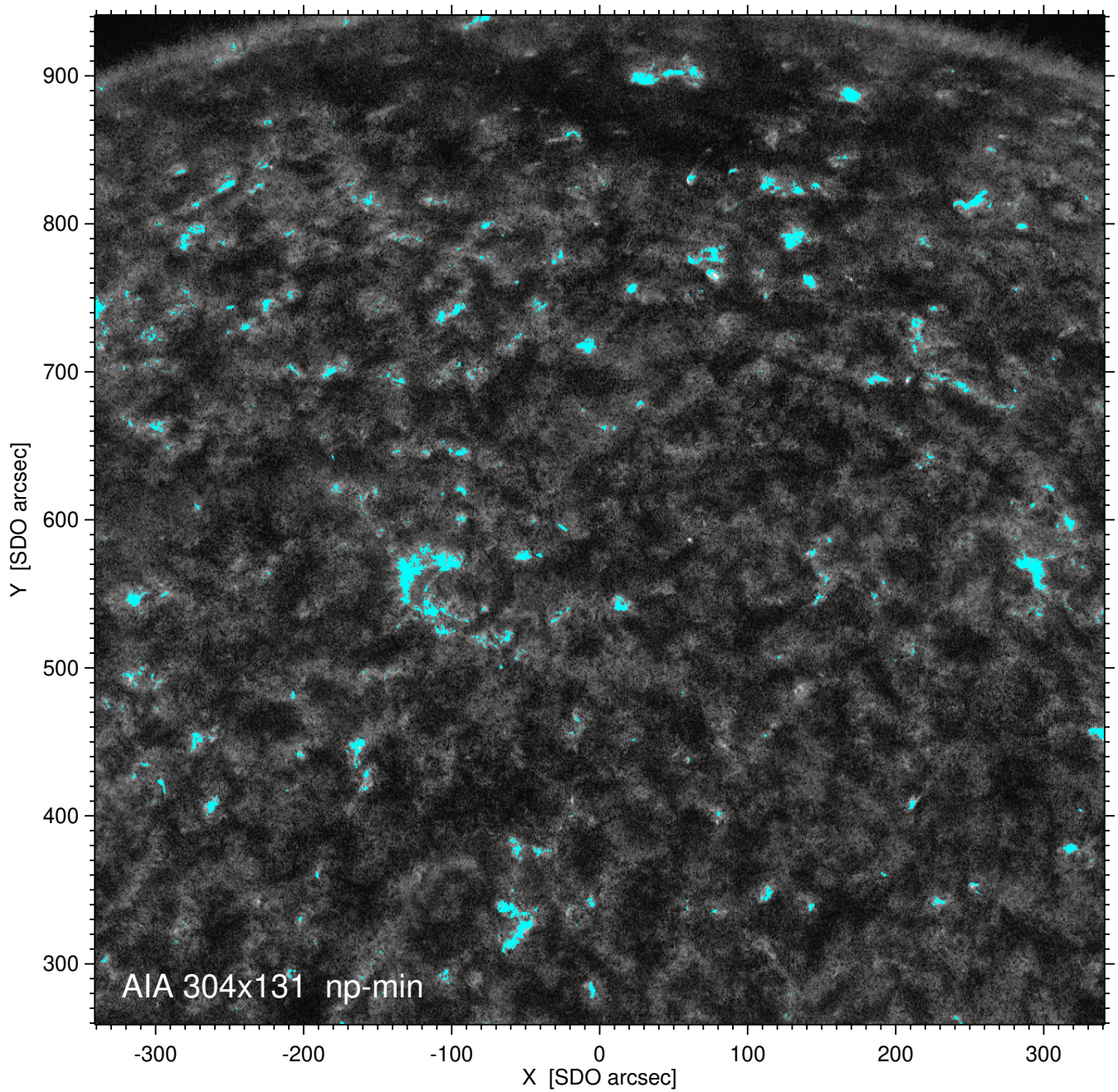


Fig. 39. SDO fire detector cutout for the same field as in the preceding figure. The small-fire density is much higher than in maximum-activity [figure 36](#).

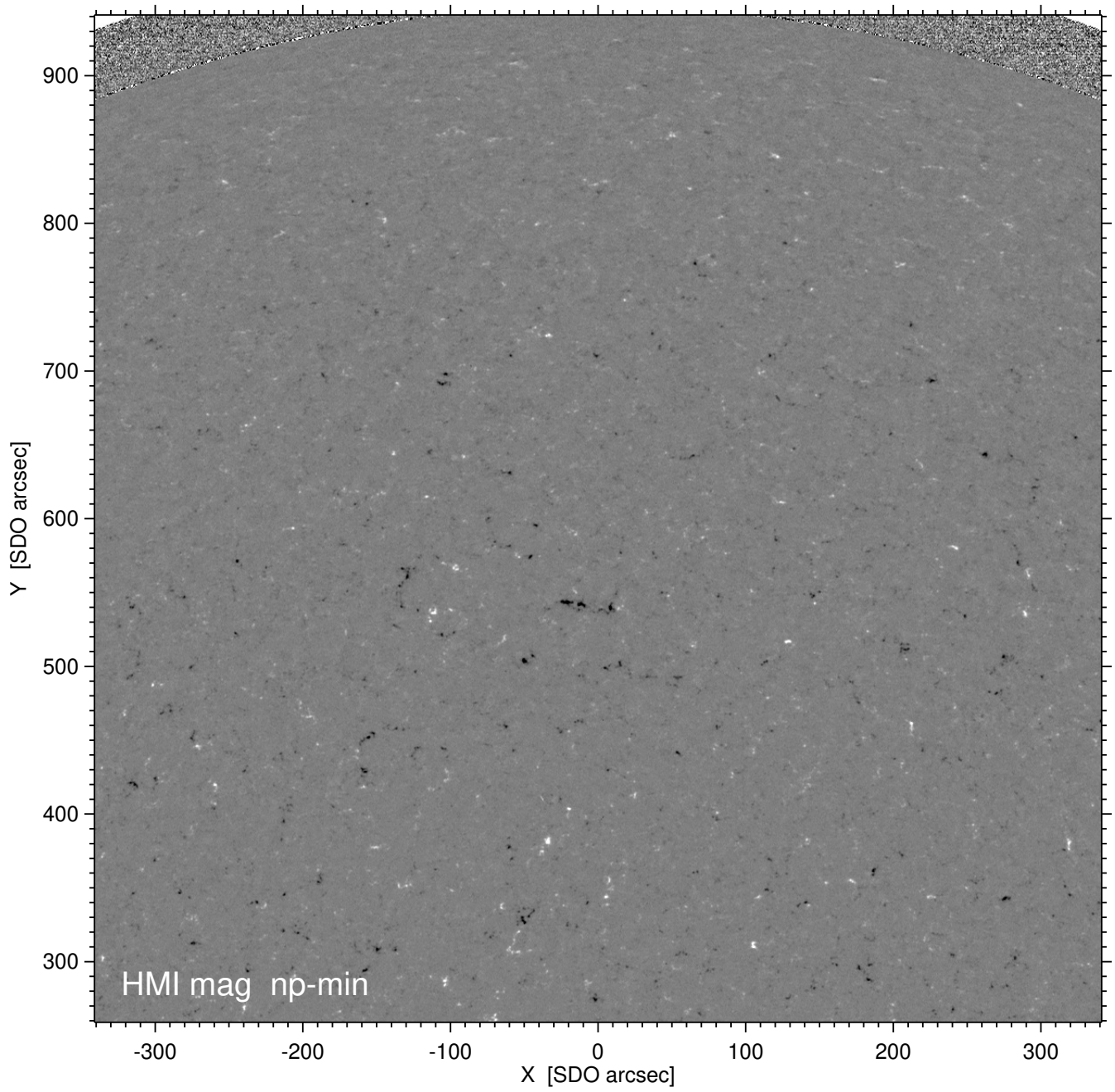


Fig. 40. HMI magnetogram for the field in the two preceding figures.

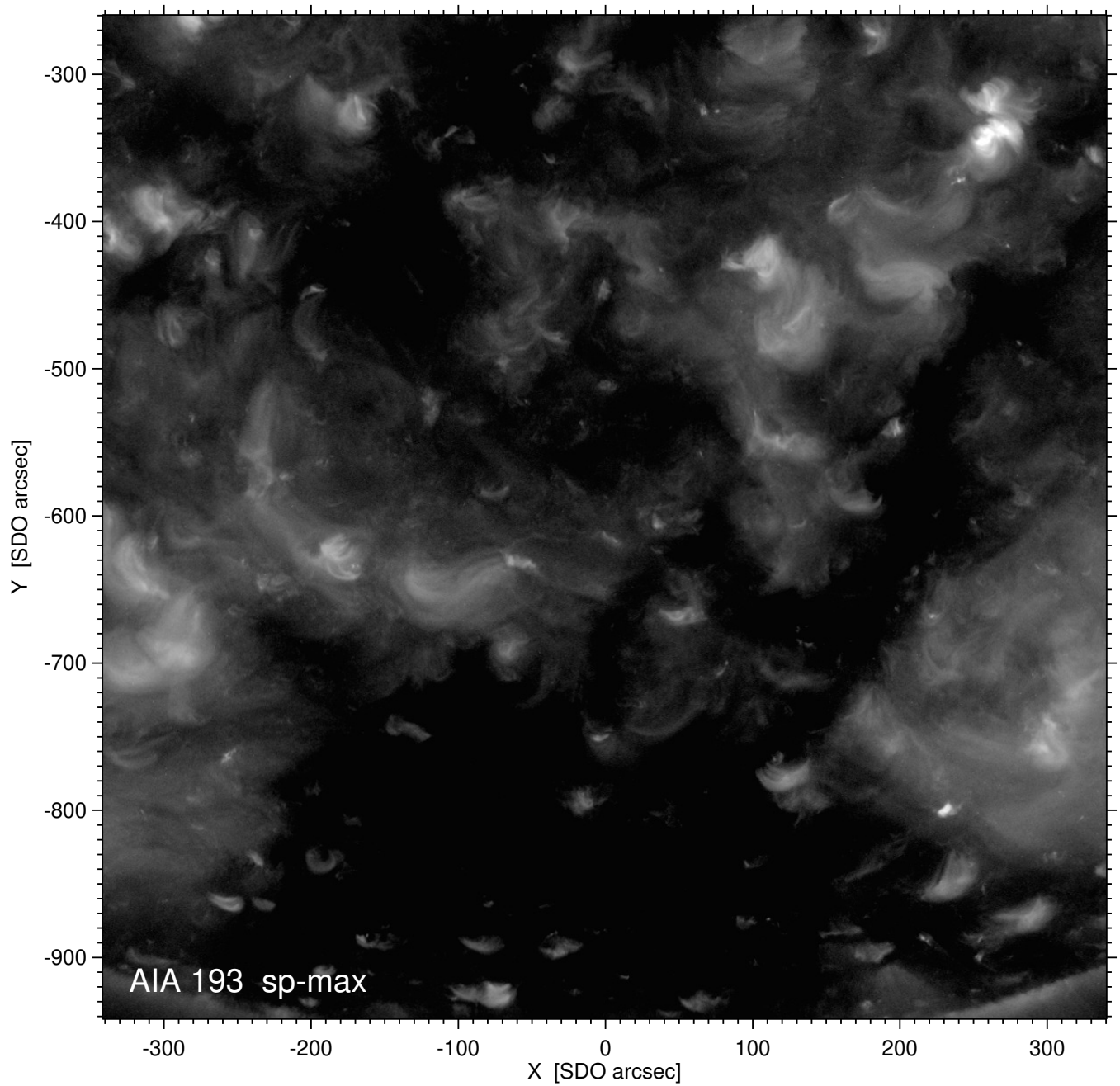


Fig. 41. AIA 193 Å cutout near the solar South pole on April 1, 2014 at 00:00 UT.

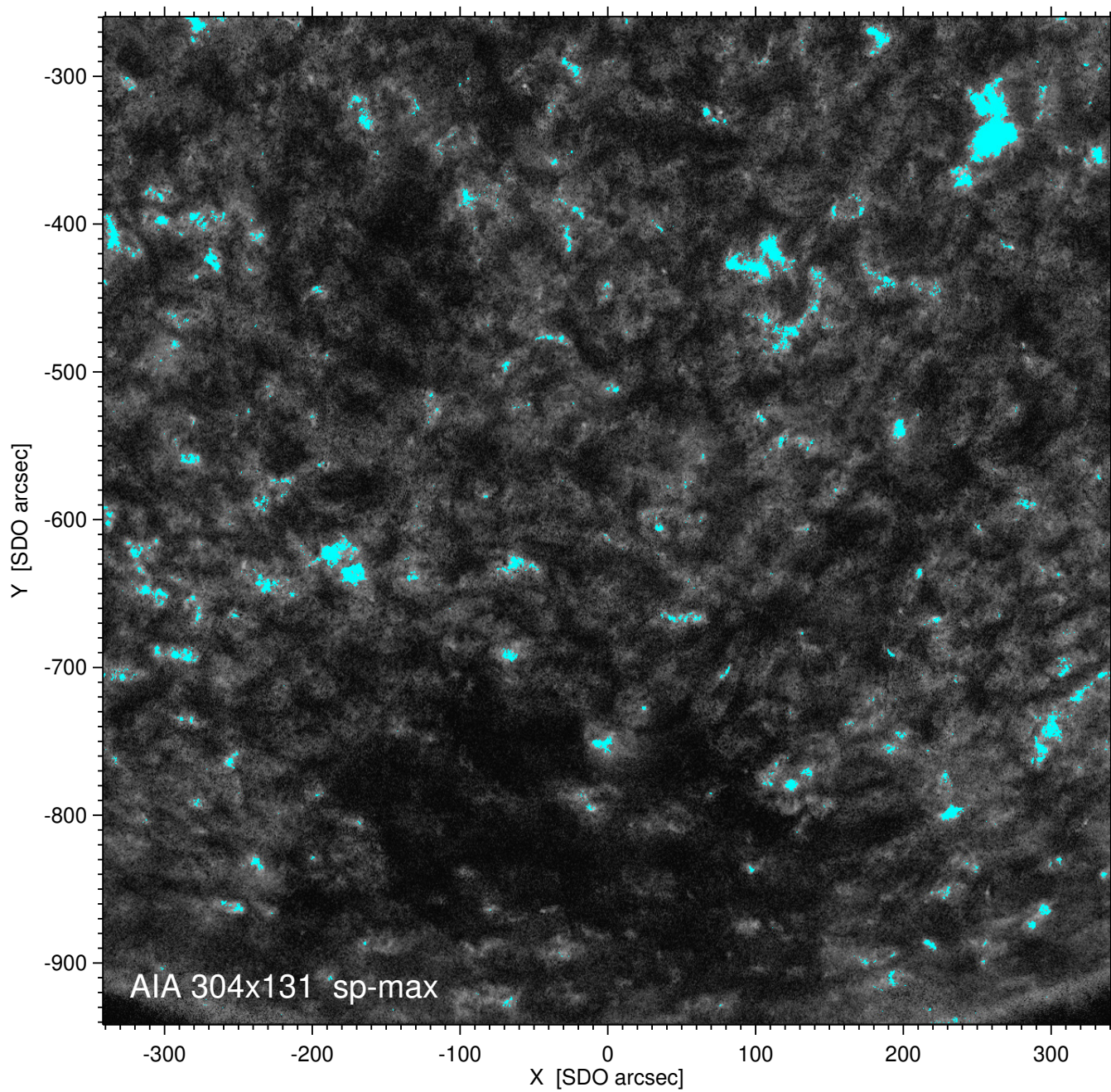


Fig. 42. SDO fire detector cutout for the same field as in the preceding figure. High fire warning, less in the polar hole.

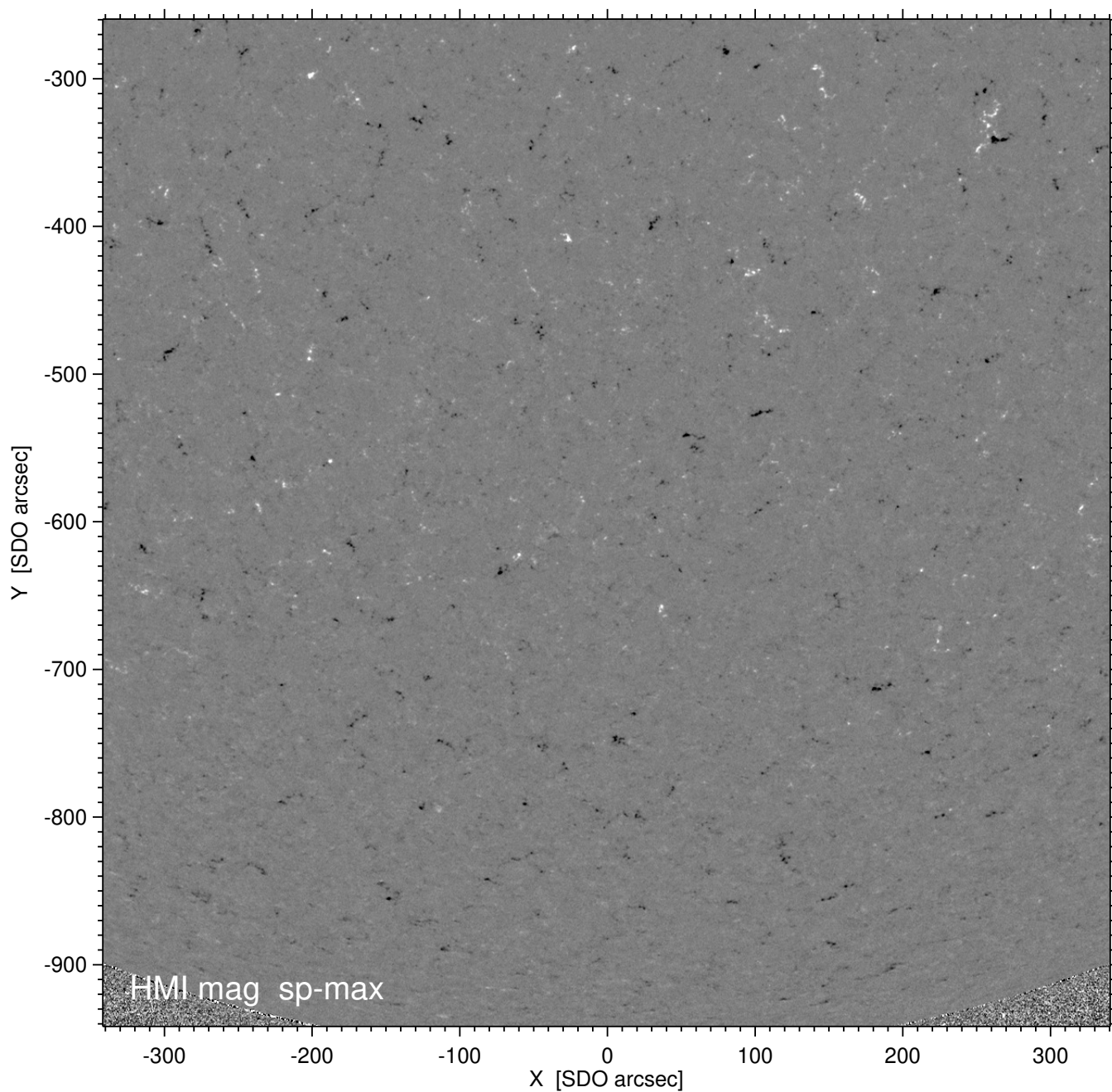


Fig. 43. HMI magnetogram for the field in the two preceding figures.

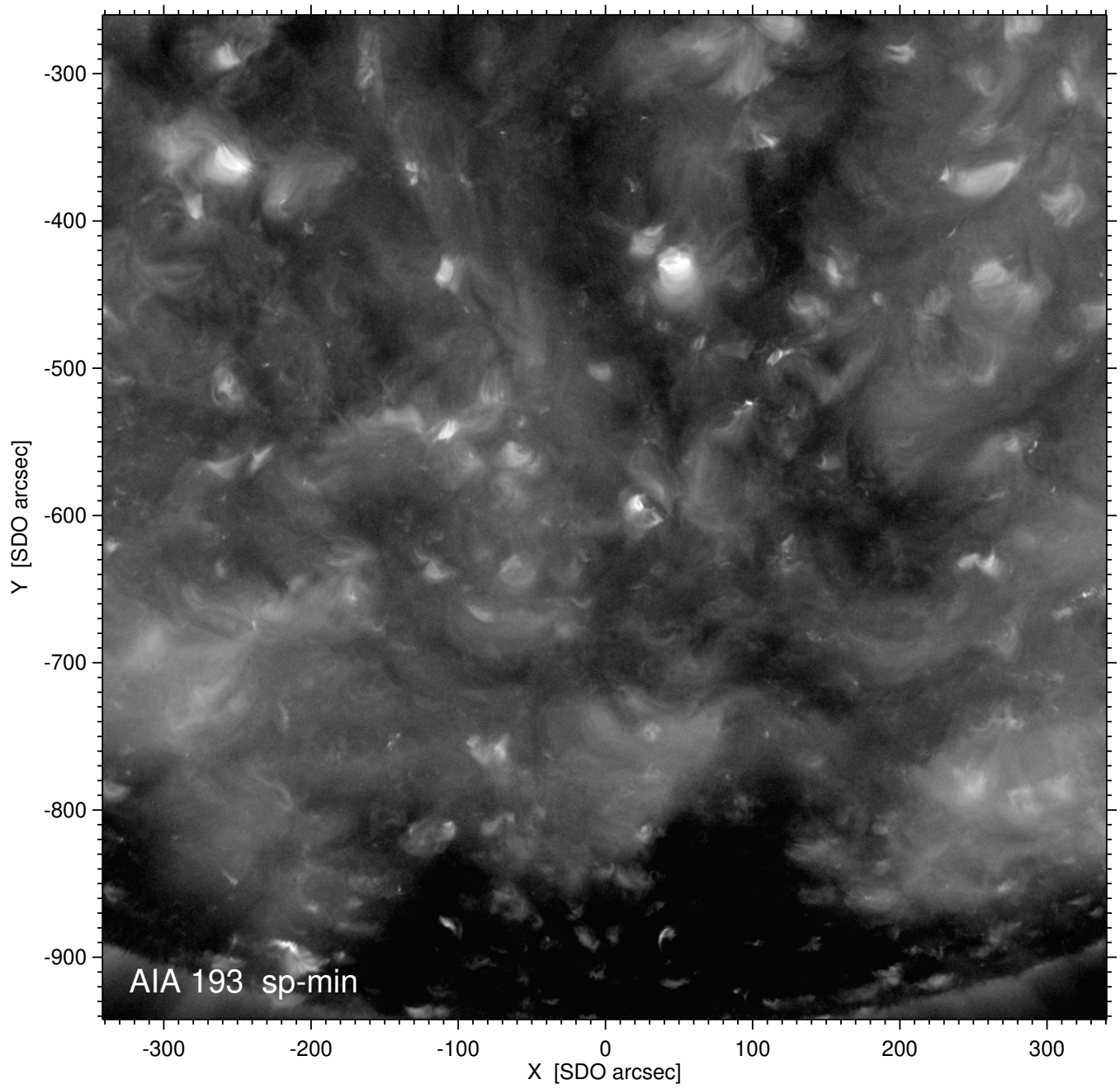


Fig. 44. AIA 193 Å cutout near the solar South pole on June 1, 2019 at 00:00 UT.

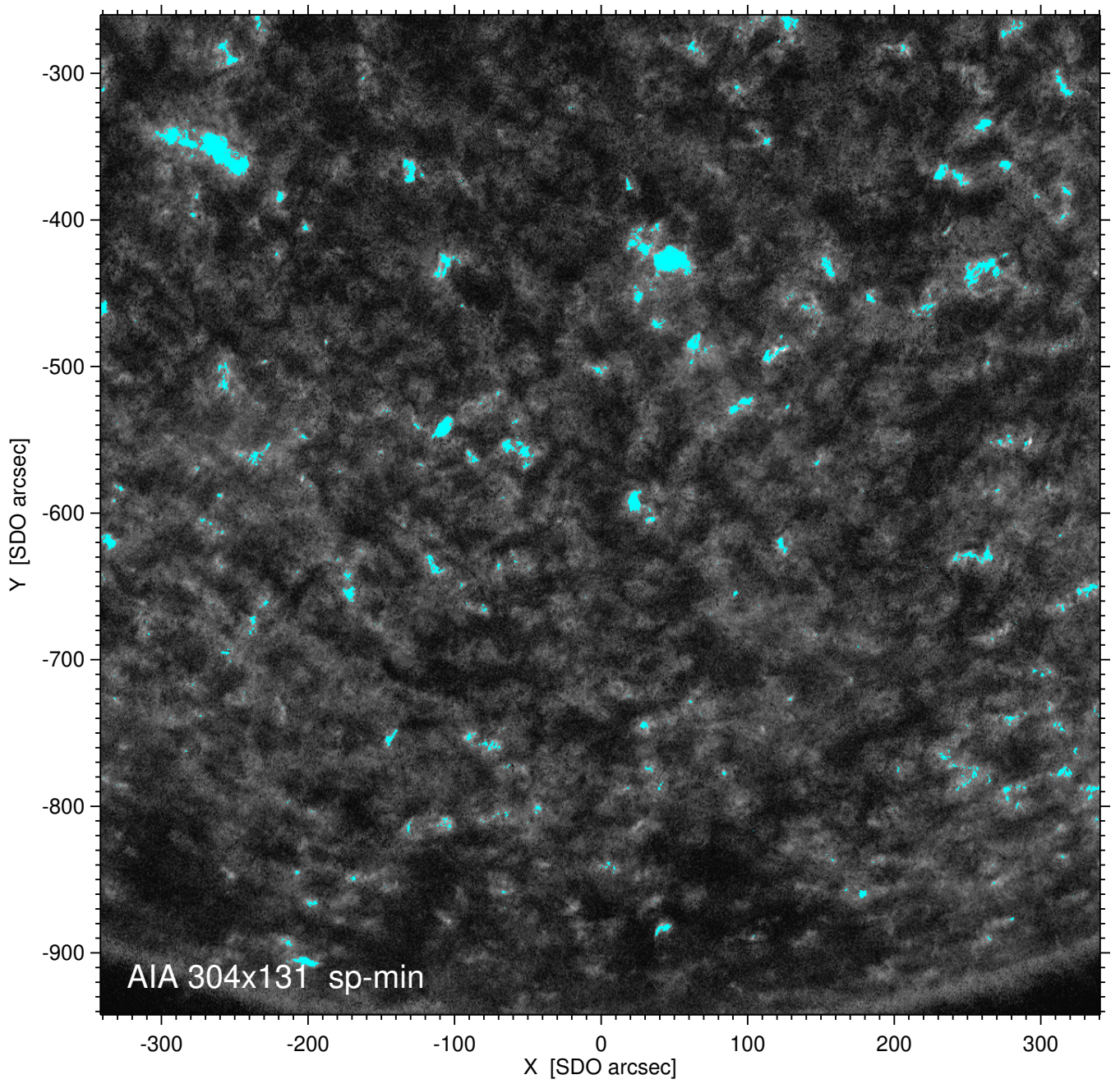


Fig. 45. SDO fire detector cutout for the same field as in the preceding figure.

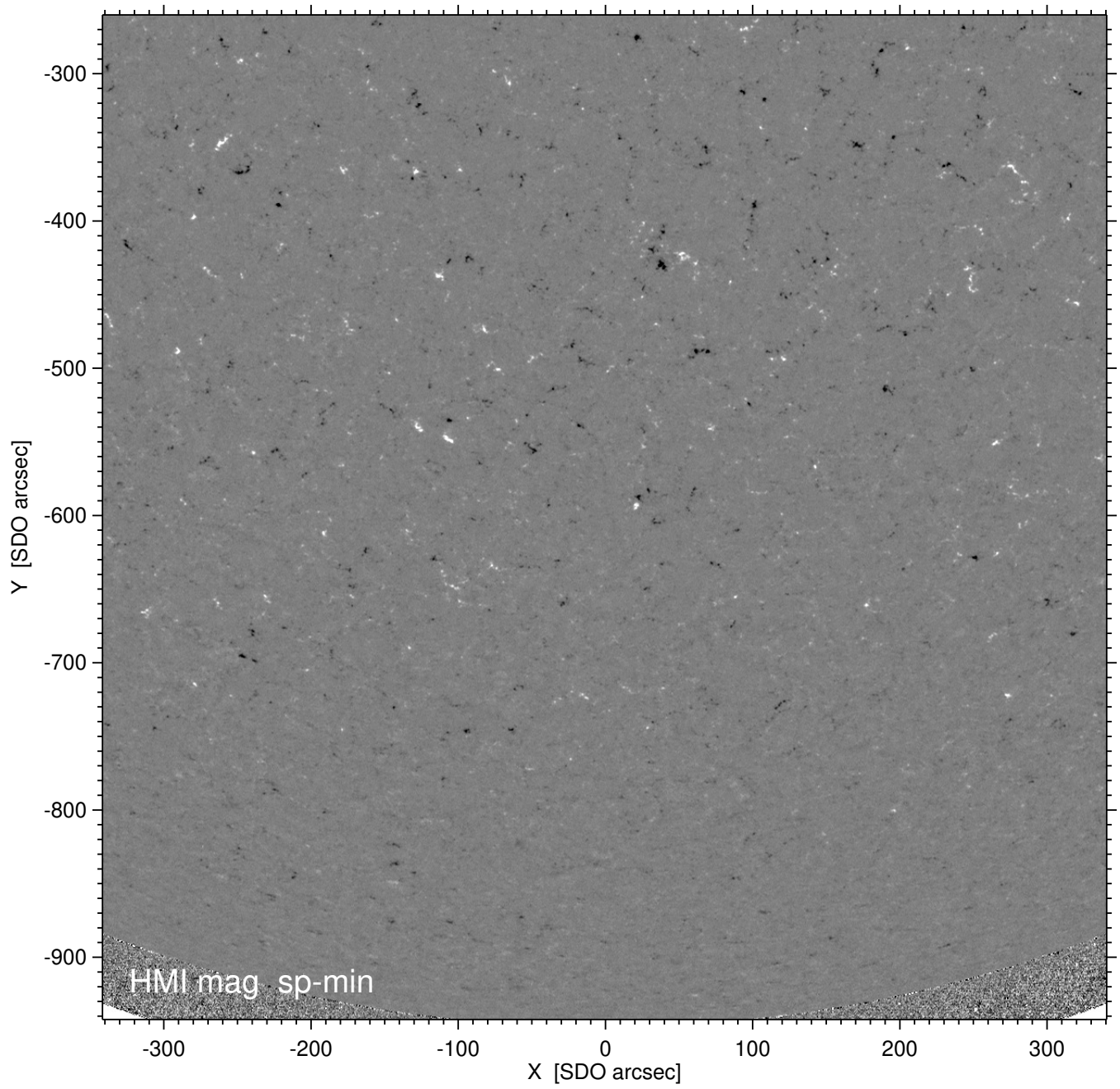


Fig. 46. HMI magnetogram for the field in the two preceding figures.

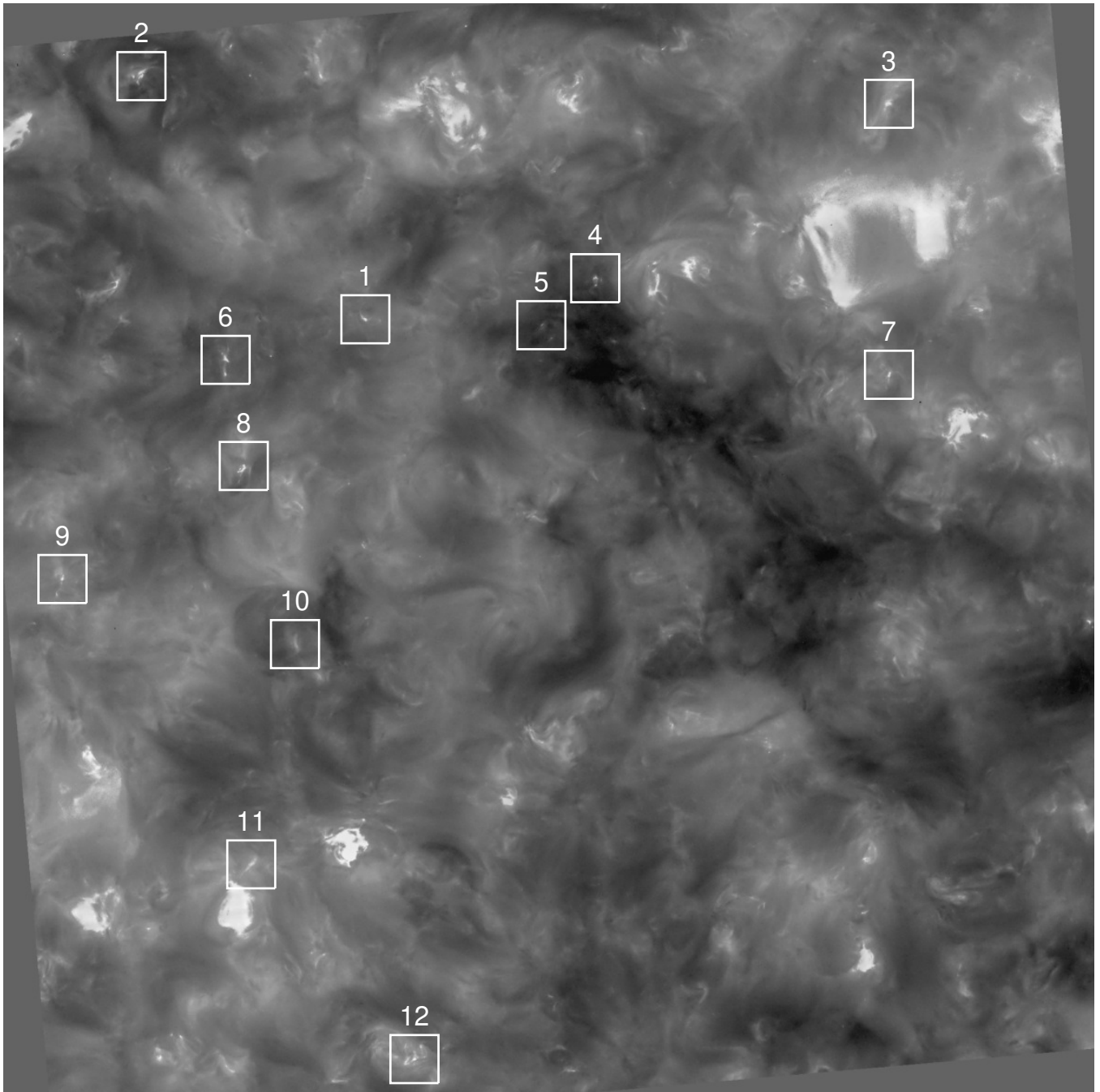


Fig. 47. The rotated $\text{SoLO } 174 \text{ \AA}$ image with superimposed ROI boxes for the campfire cutouts. ROI-1 is the campfire that was marked in the annotated version in the press-release material. The others are eye-ball selected in top-to-bottom order, also including small bright patches with more complex than single-flame morphology.

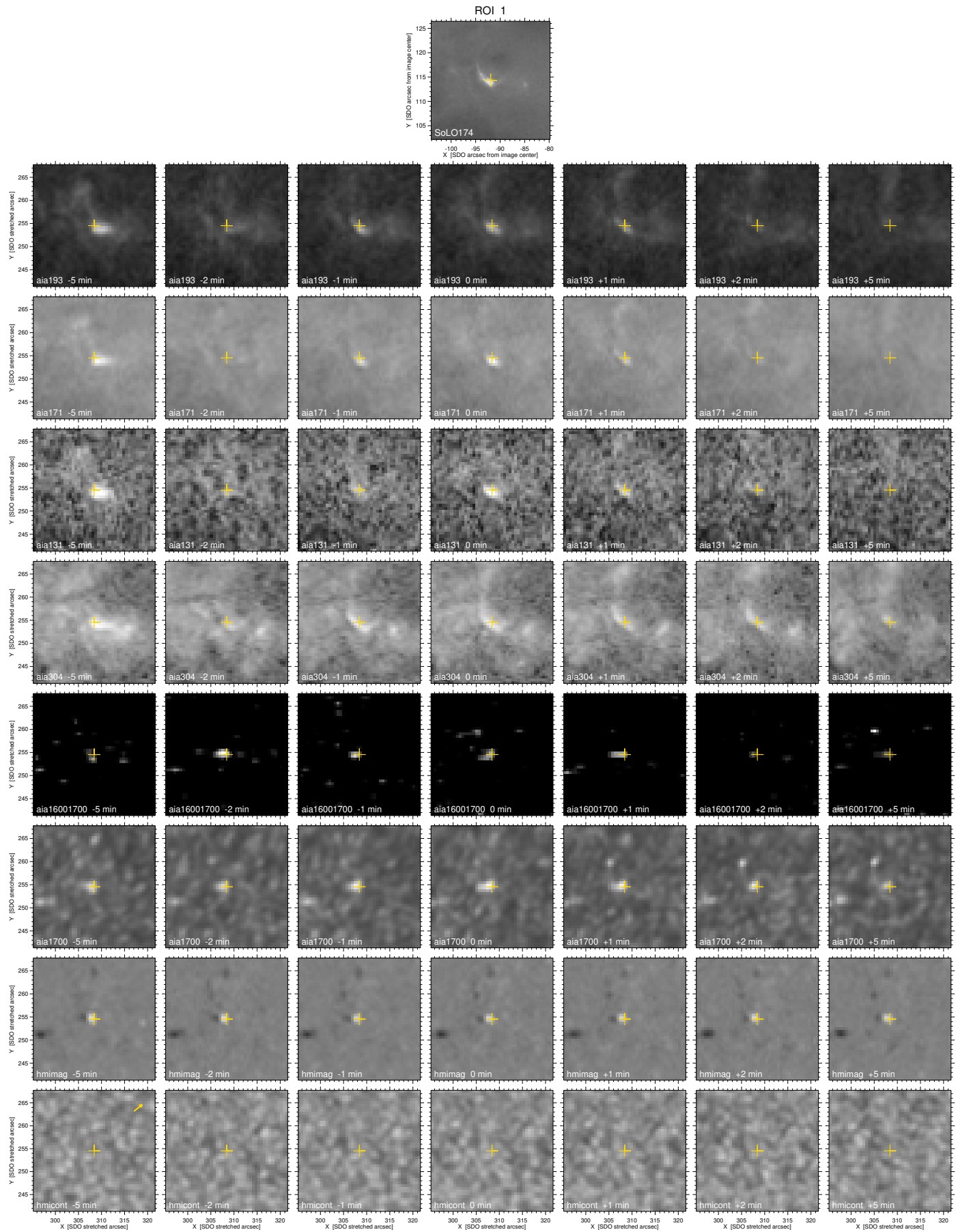


Fig. 48. Cutouts for ROI-1. Format details are given in the main text in [section 6](#). This SoLO campfire (top) was annotated as exemplary in the press release. It was also present in the AIA EUV images, also recurrently before, best in AIA 304 Å. There was a bipolar MC pair on the surface underneath, with enhanced brightening in the UV including excess in the 16001700 construct.

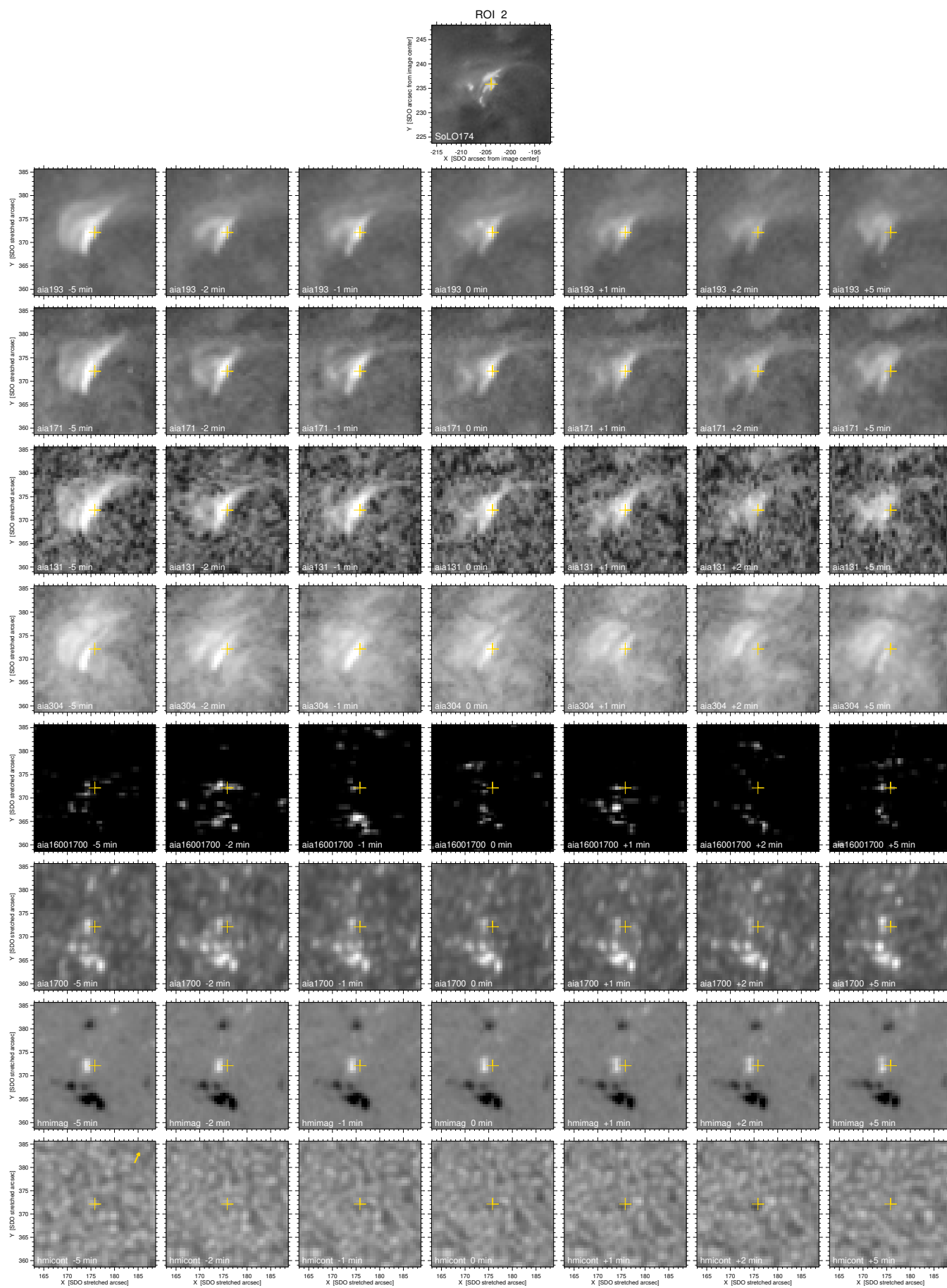


Fig. 49. Cutouts for ROI-2.

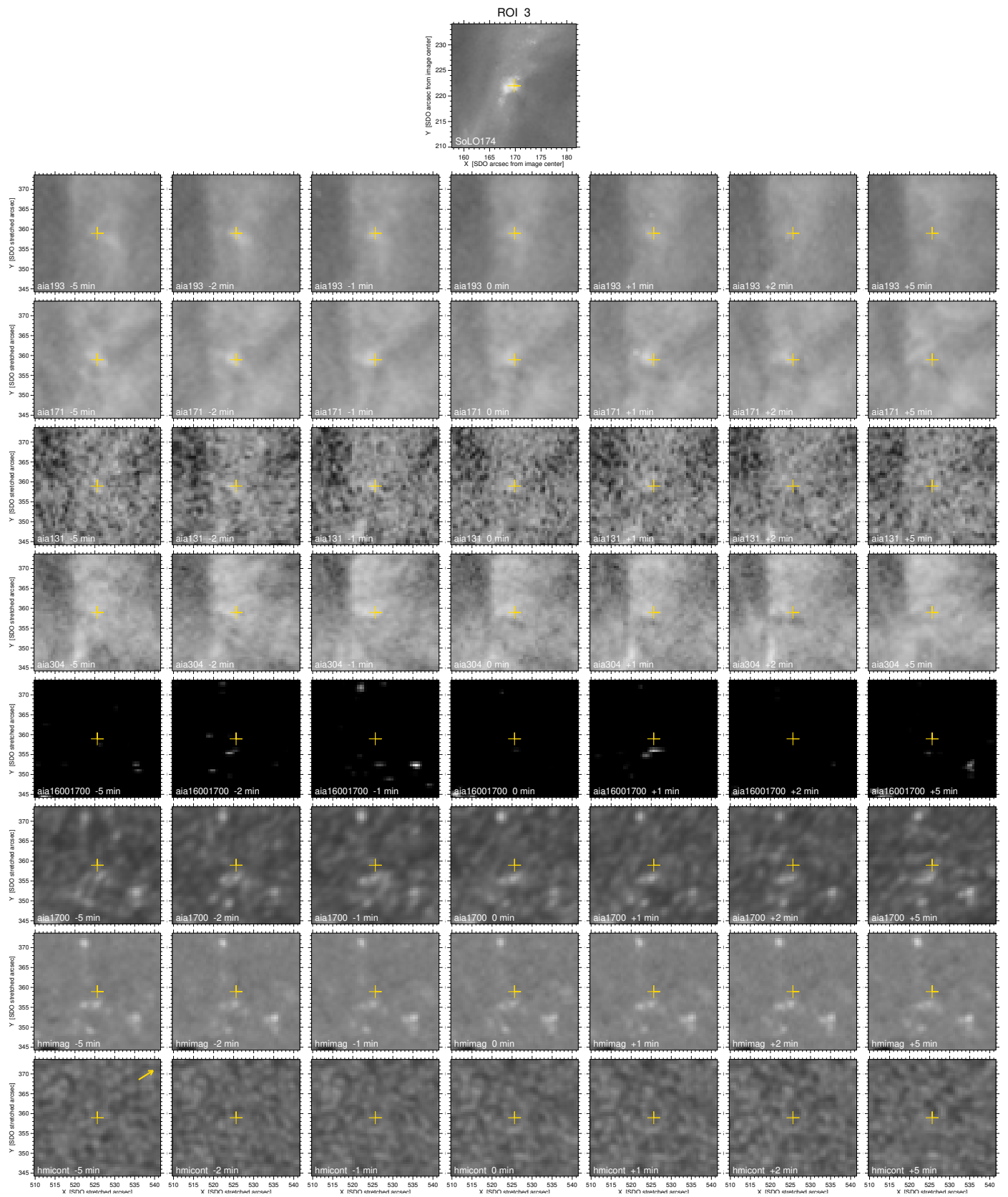


Fig. 50. Cutouts for ROI-3.

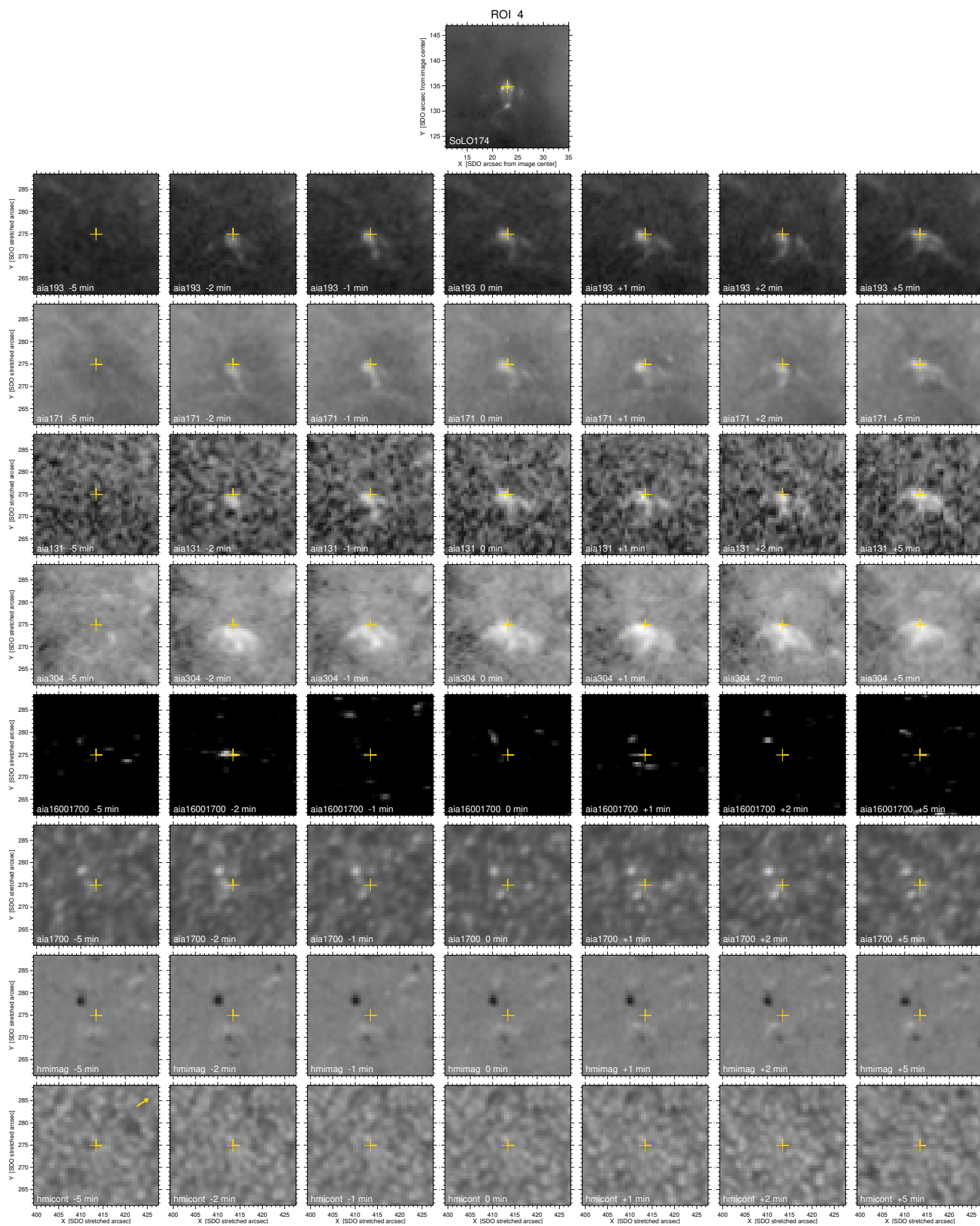


Fig. 51. Cutouts for ROI-4.

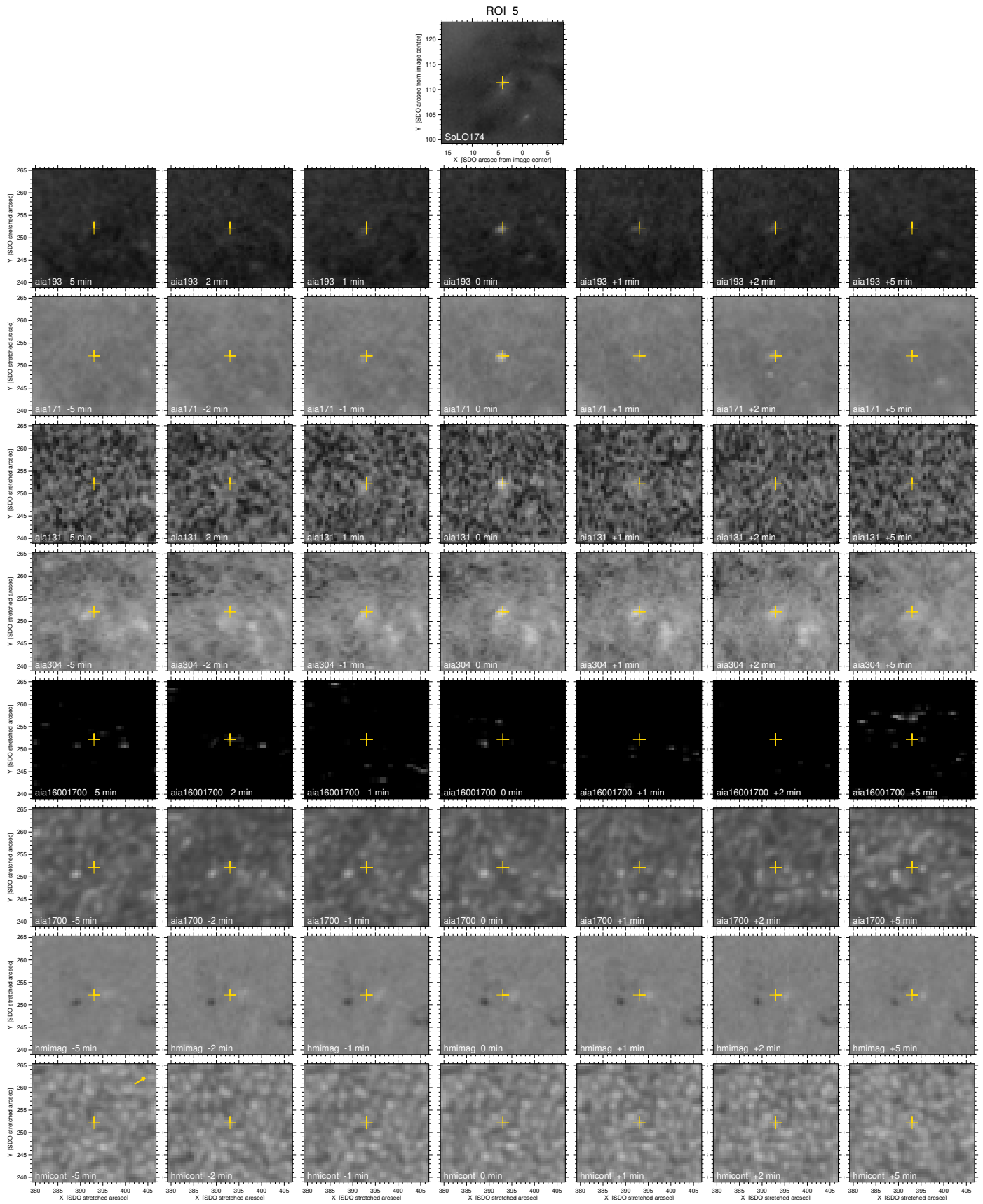


Fig. 52. Cutouts for ROI-5.

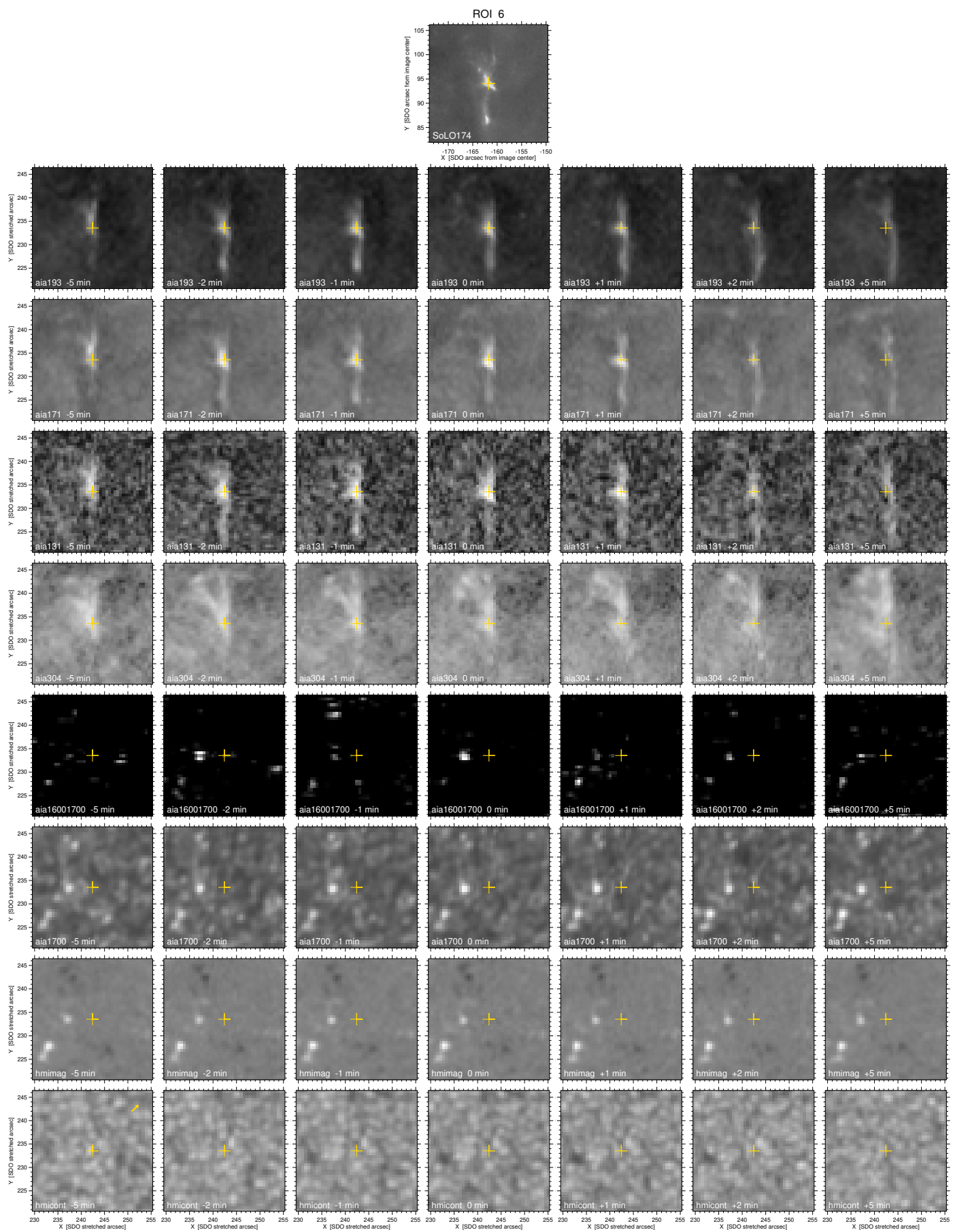


Fig. 53. Cutouts for ROI-6.

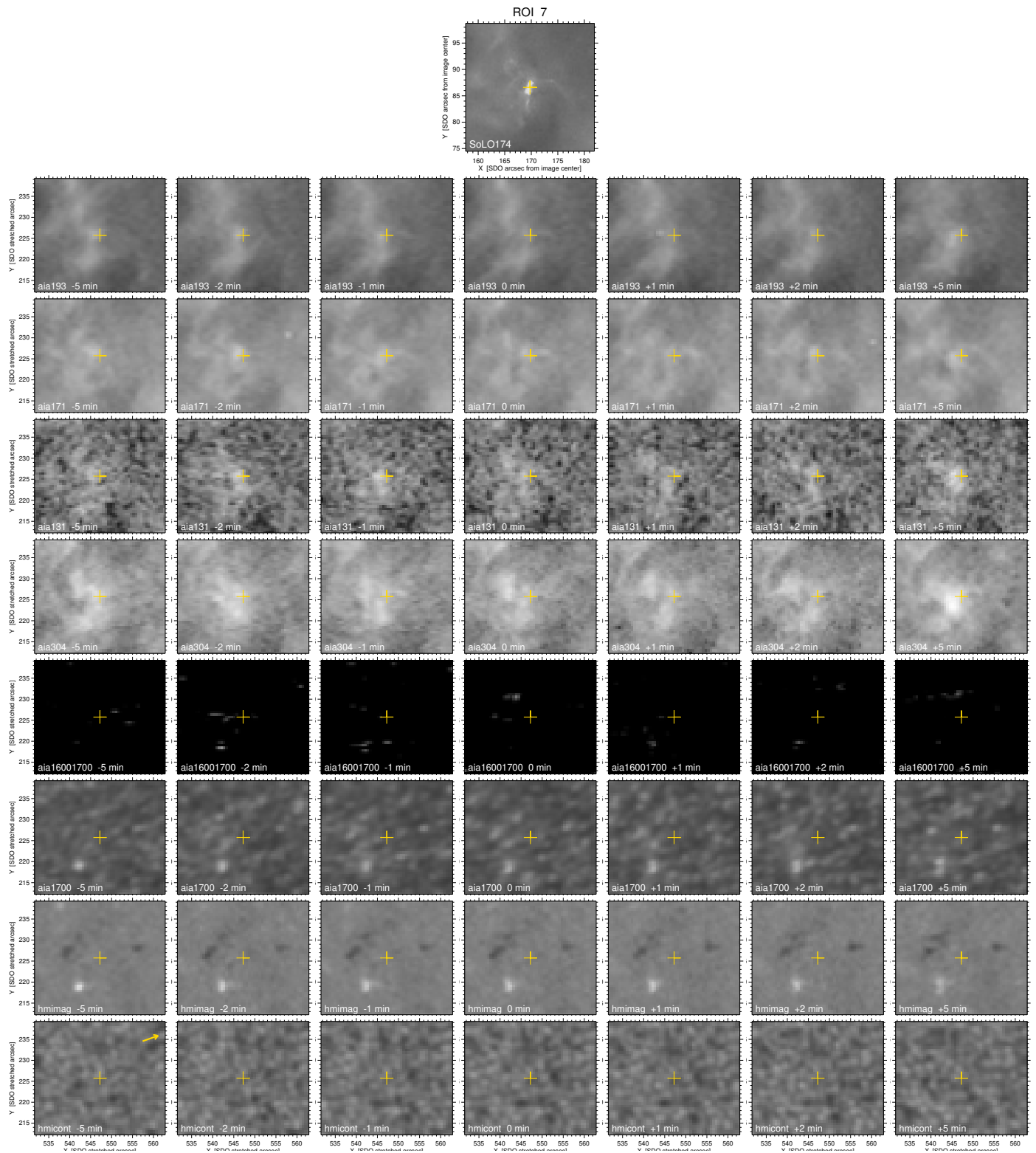


Fig. 54. Cutouts for ROI-7.

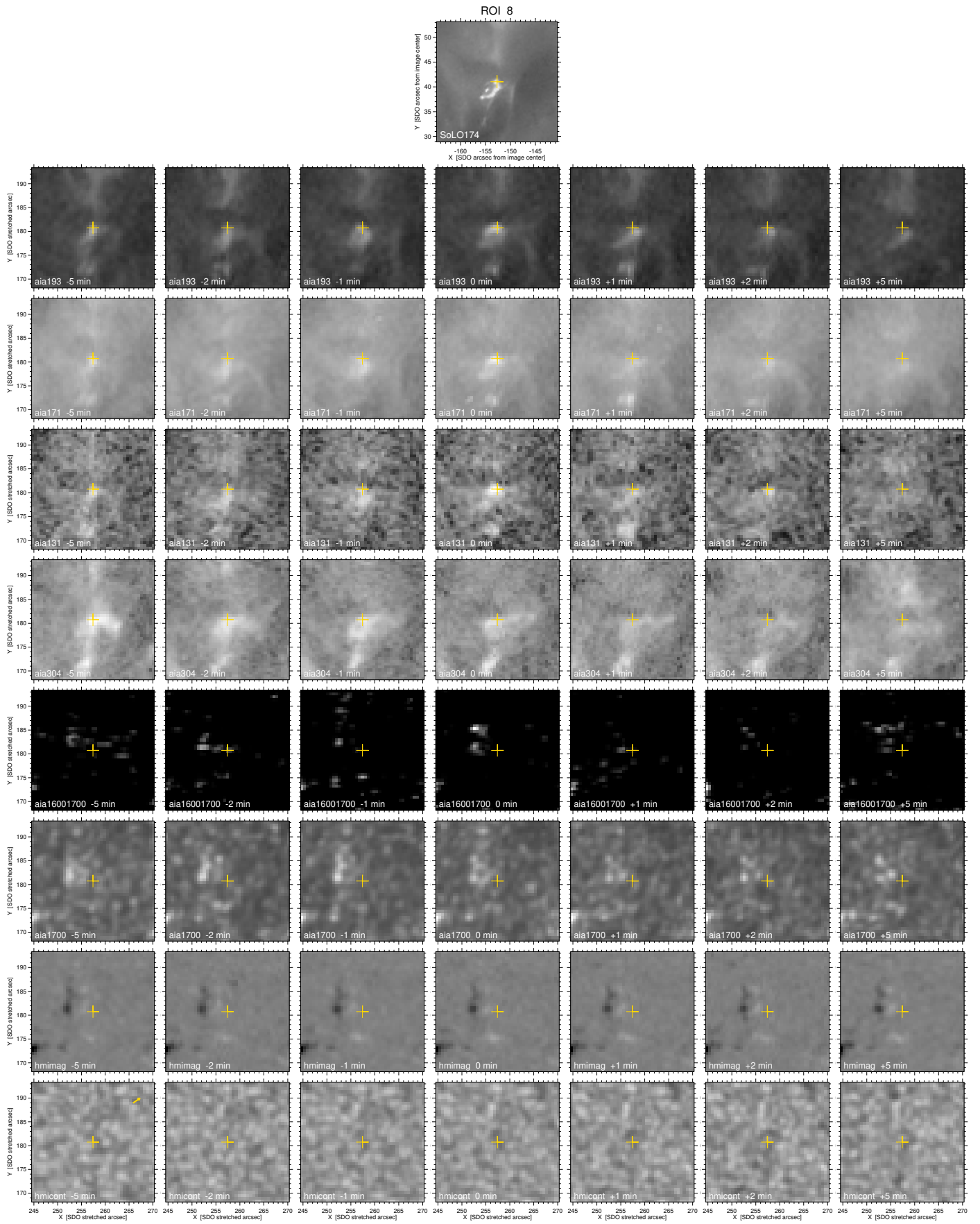


Fig. 55. Cutouts for ROI-8.

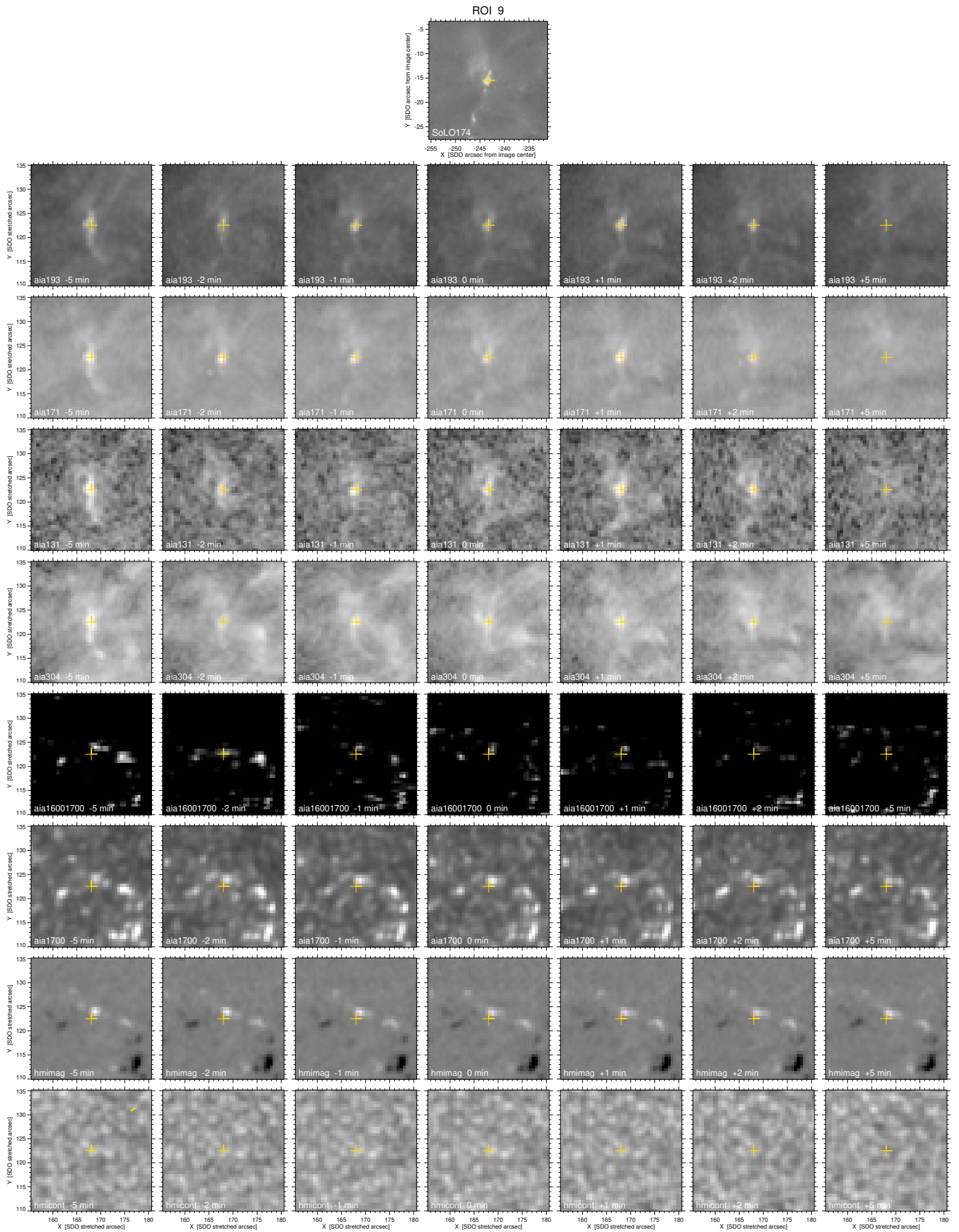


Fig. 56. Cutouts for ROI-9.

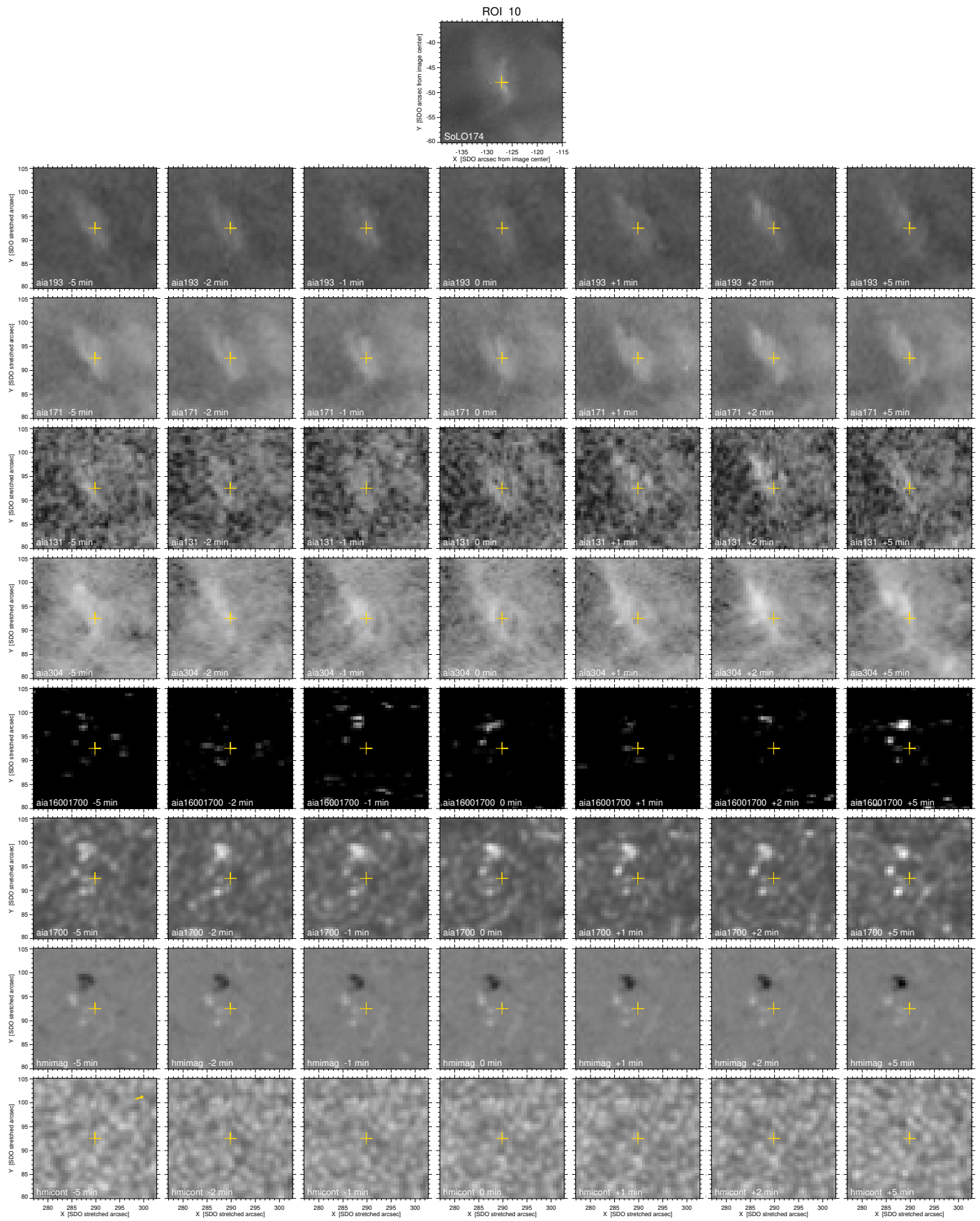


Fig. 57. Cutouts for ROI-10.

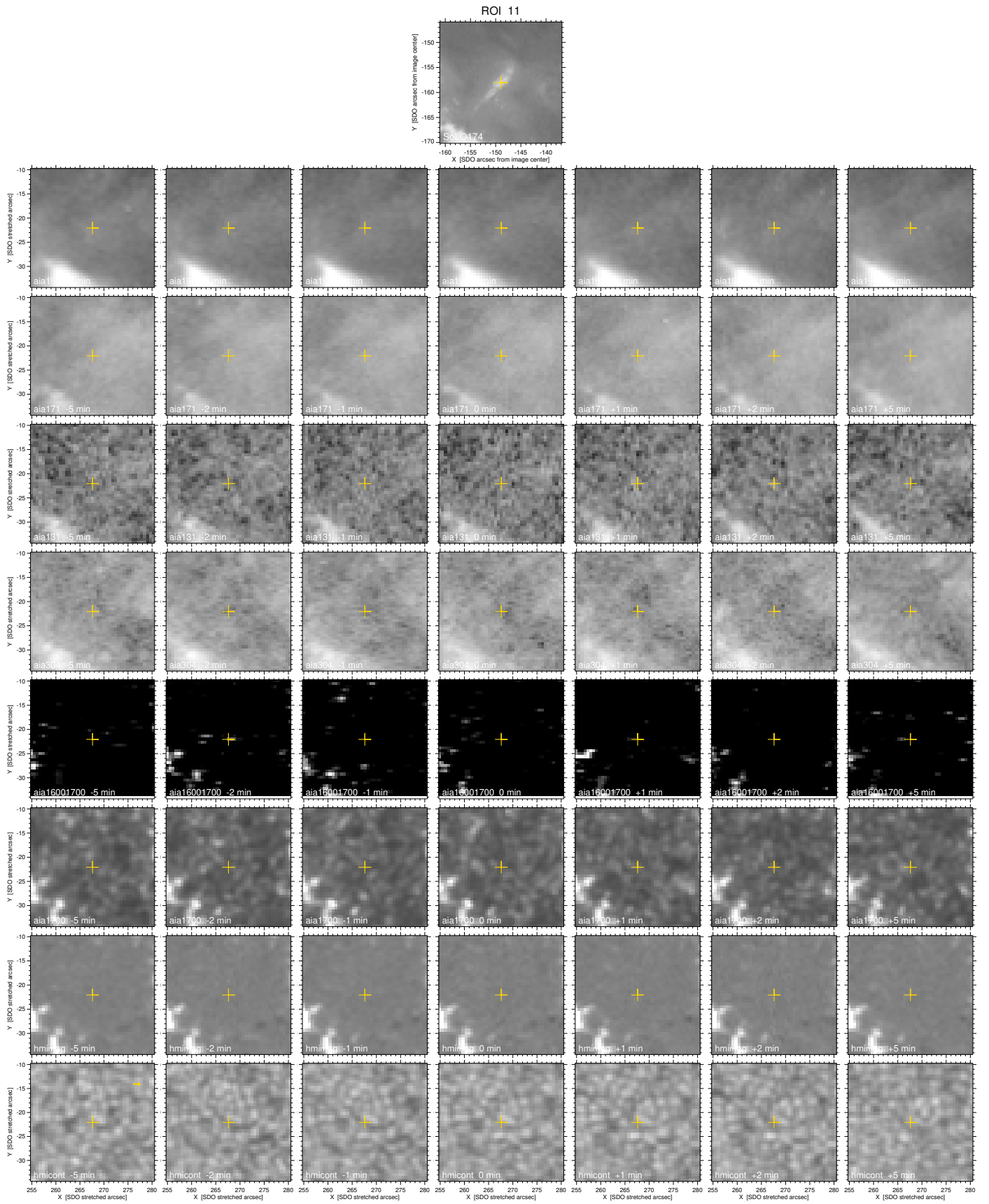


Fig. 58. Cutouts for ROI-11.

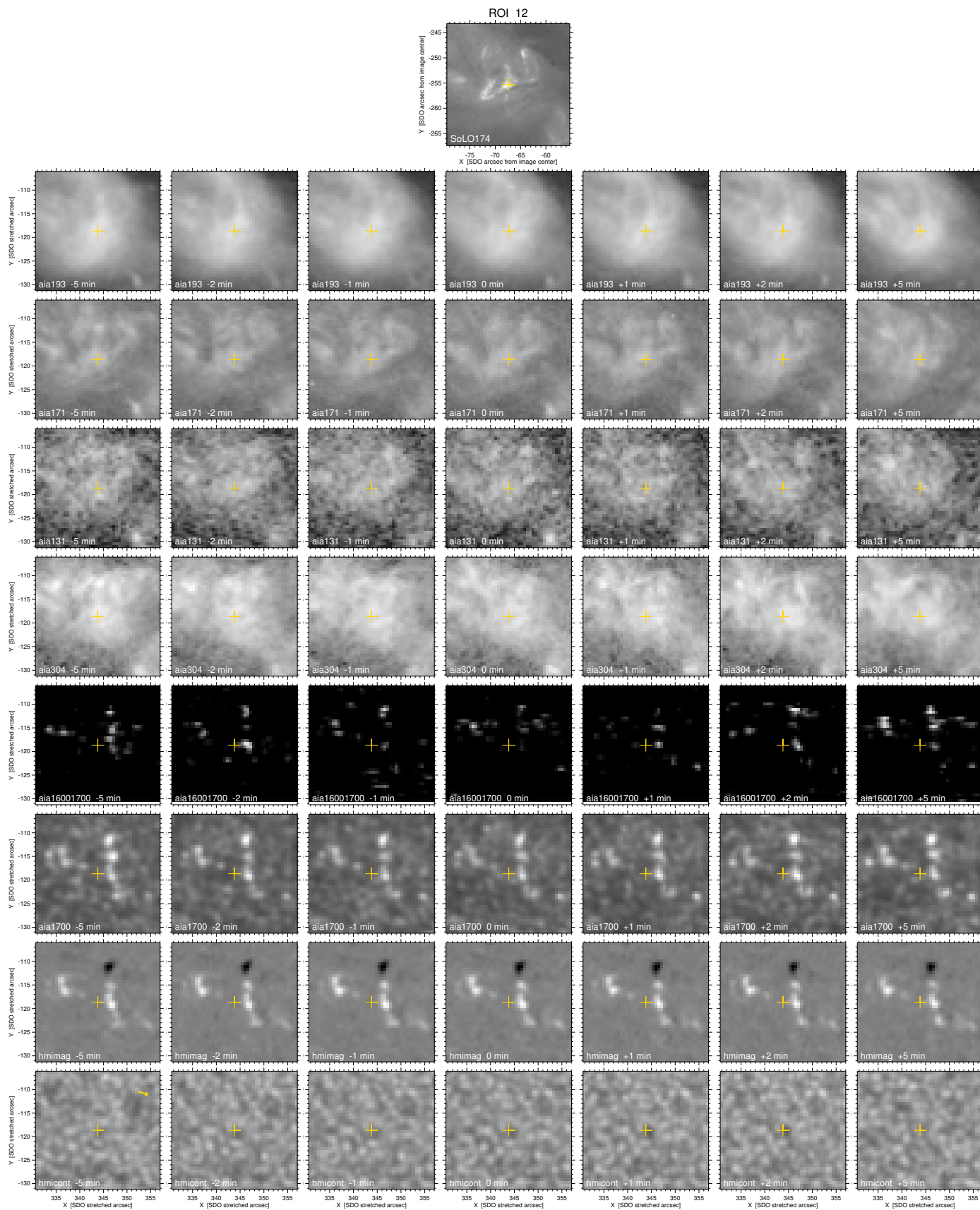


Fig. 59. Cutouts for ROI-12.

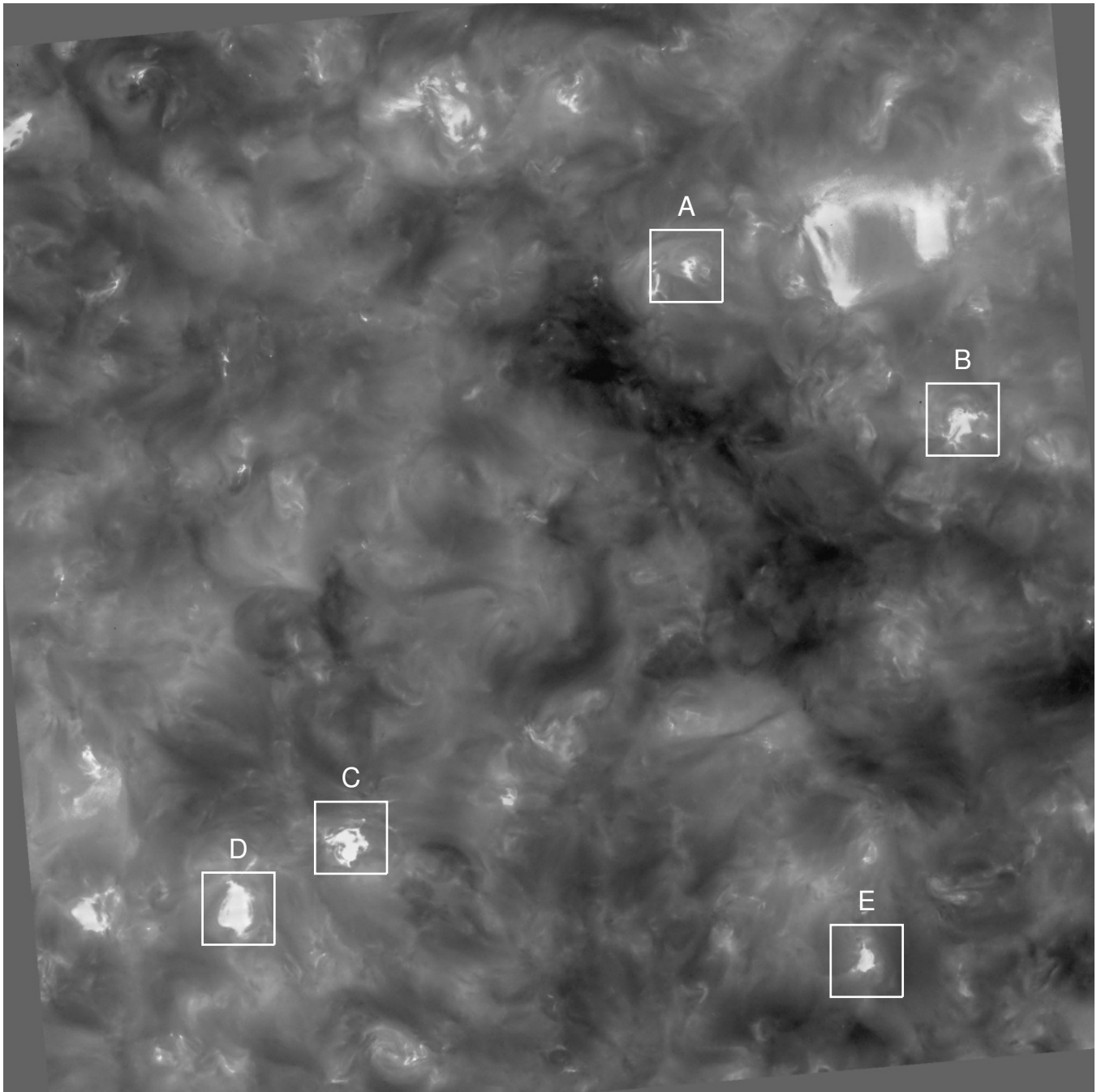


Fig. 60. The rotated SoLO 174 Å image with superimposed ROI boxes for the brushfire cutouts.

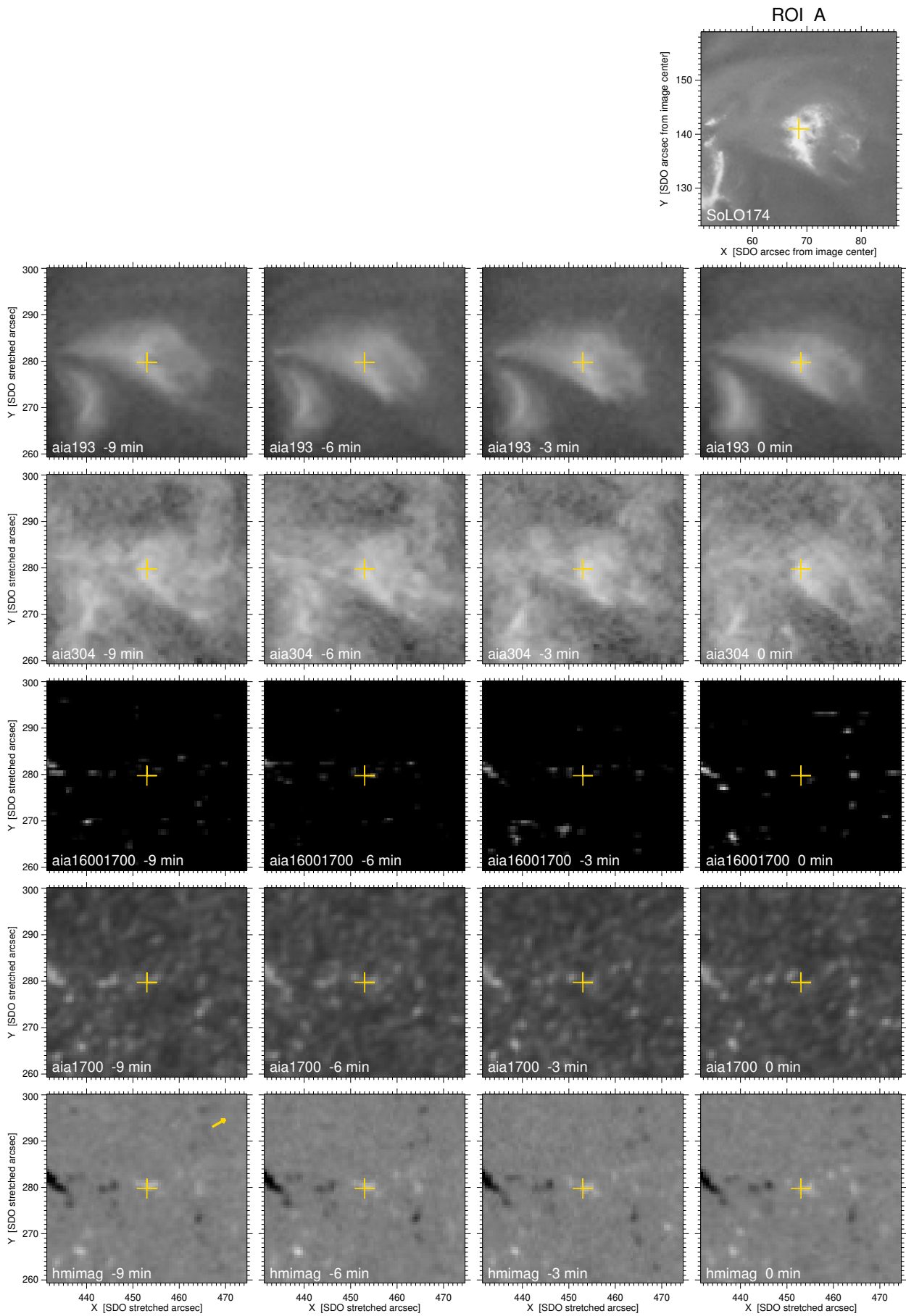


Fig. 61. Cutouts for ROI-A.

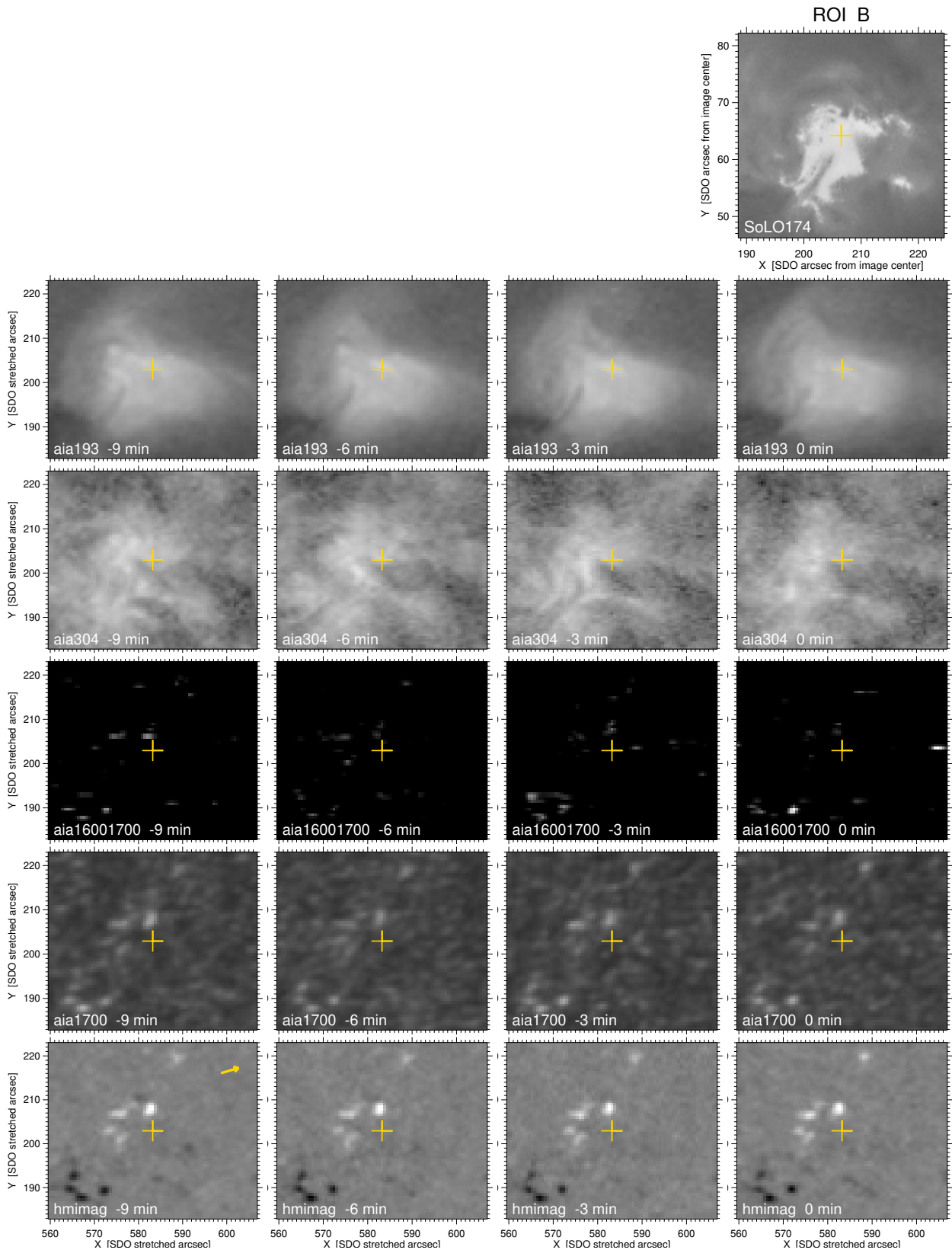


Fig. 62. Cutouts for ROI-B.

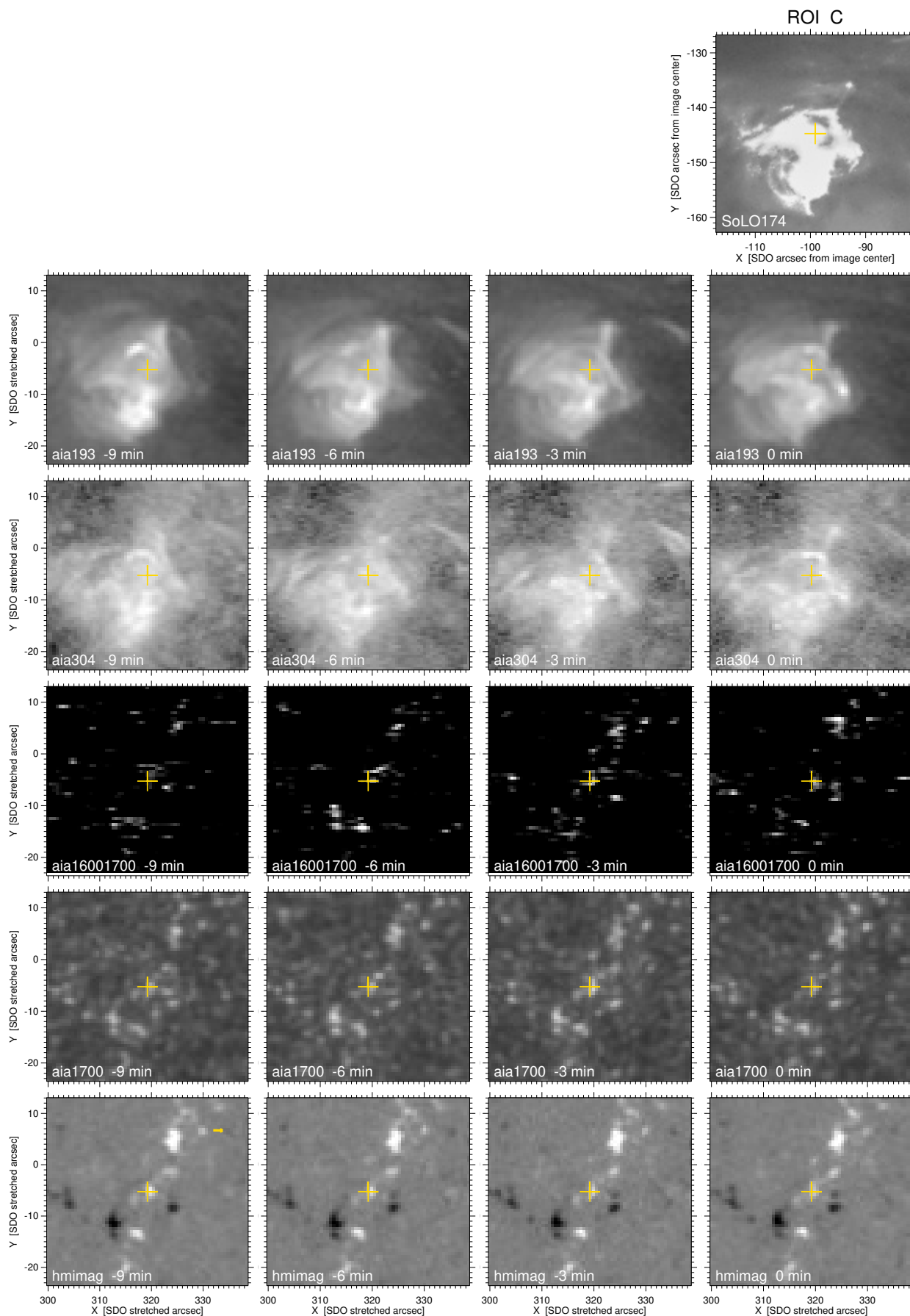


Fig. 63. Cutouts for ROI-C.

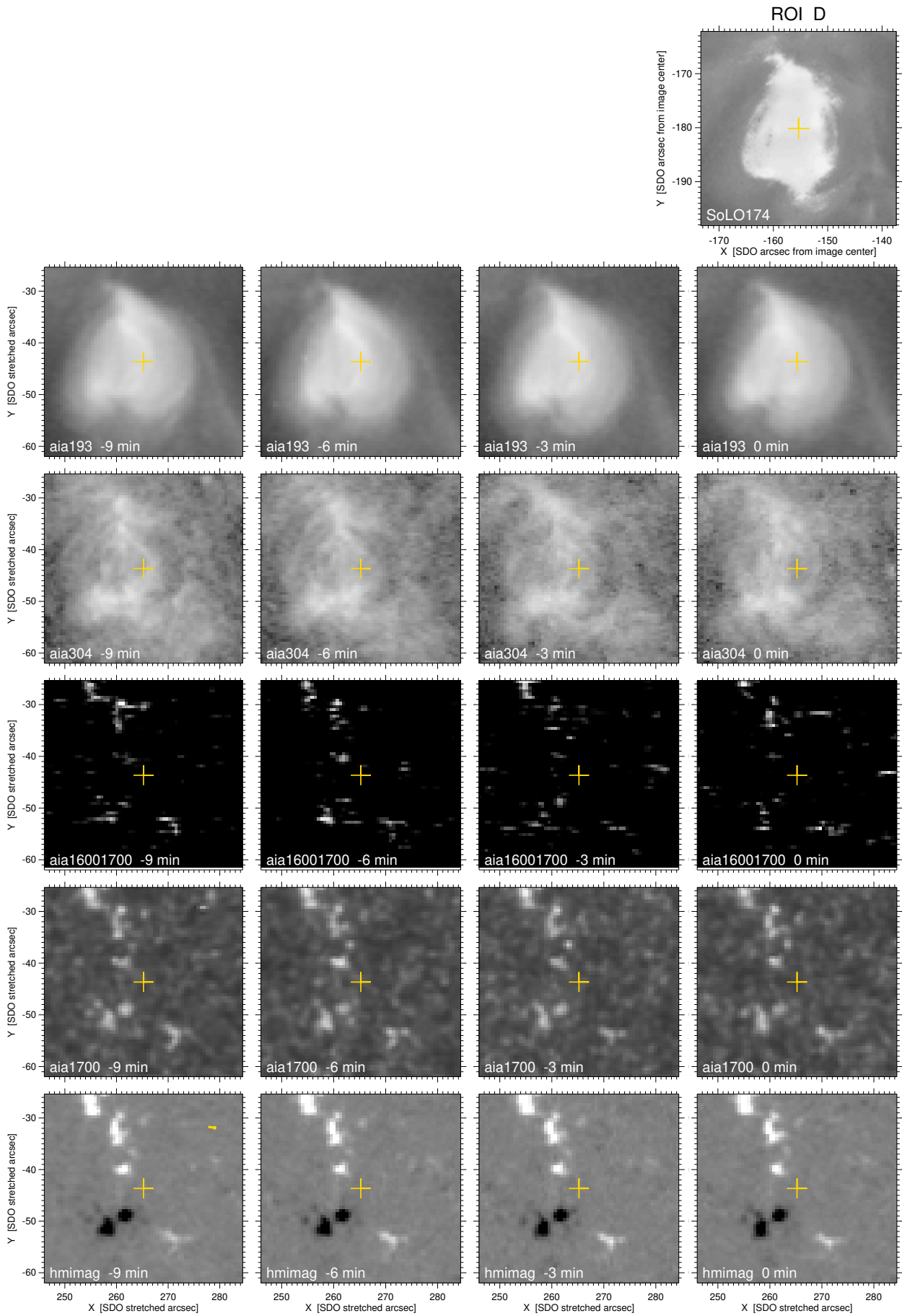


Fig. 64. Cutouts for ROI-D.

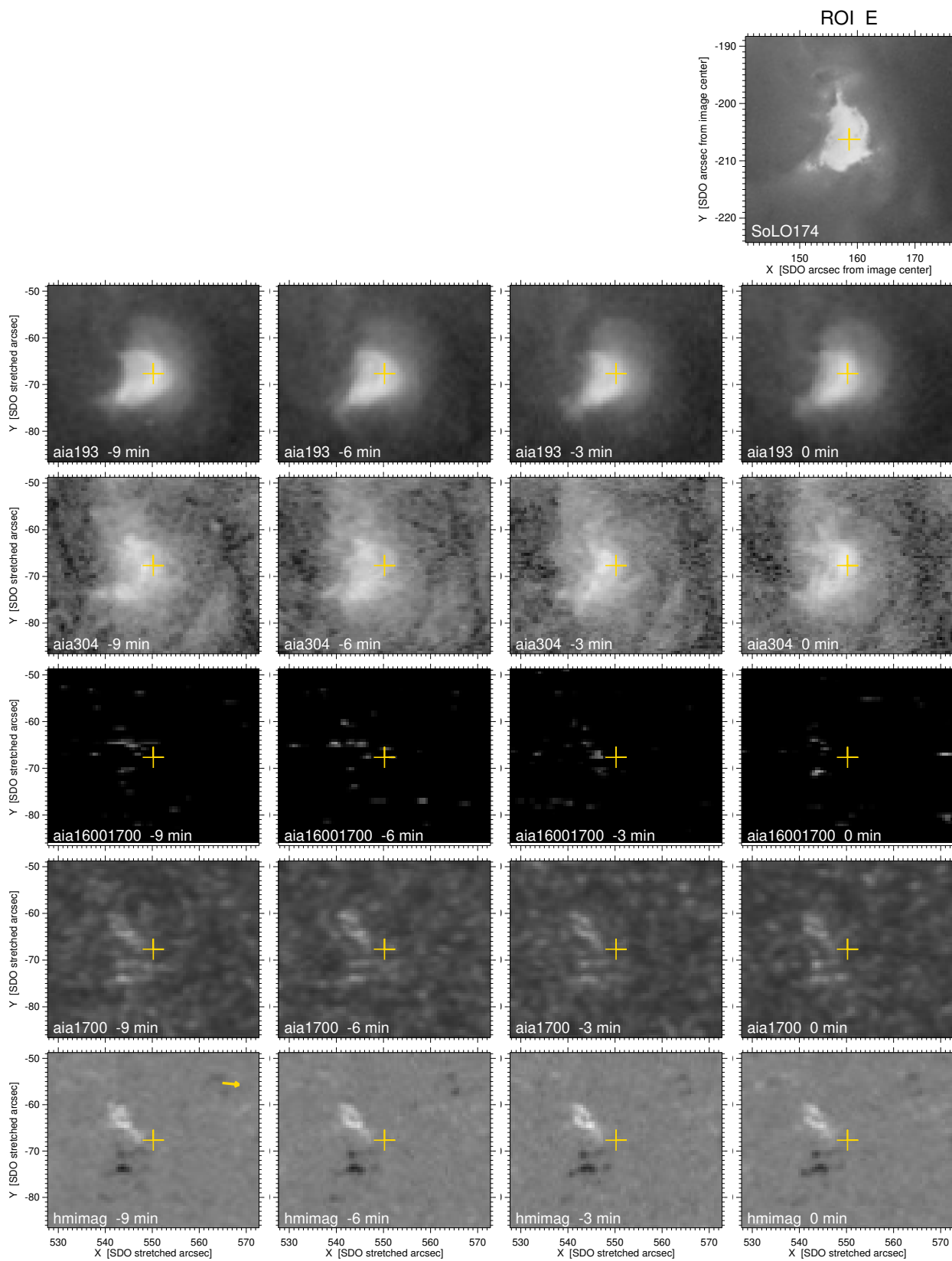


Fig. 65. Cutouts for ROI-E.

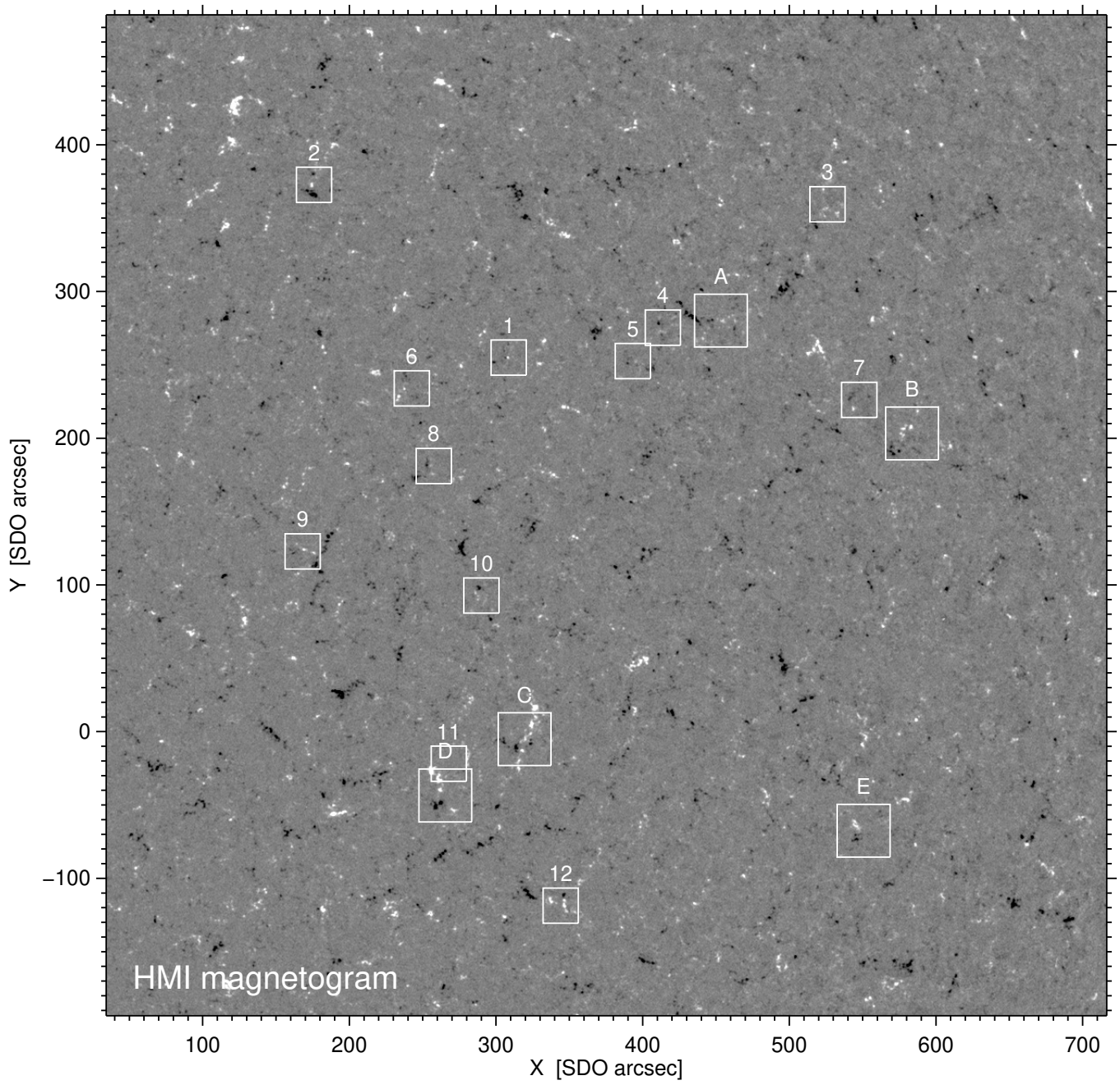


Fig. 66. The HMI magnetogram at best-match time with superimposed ROI boxes for all campfire and brushfire cutouts.

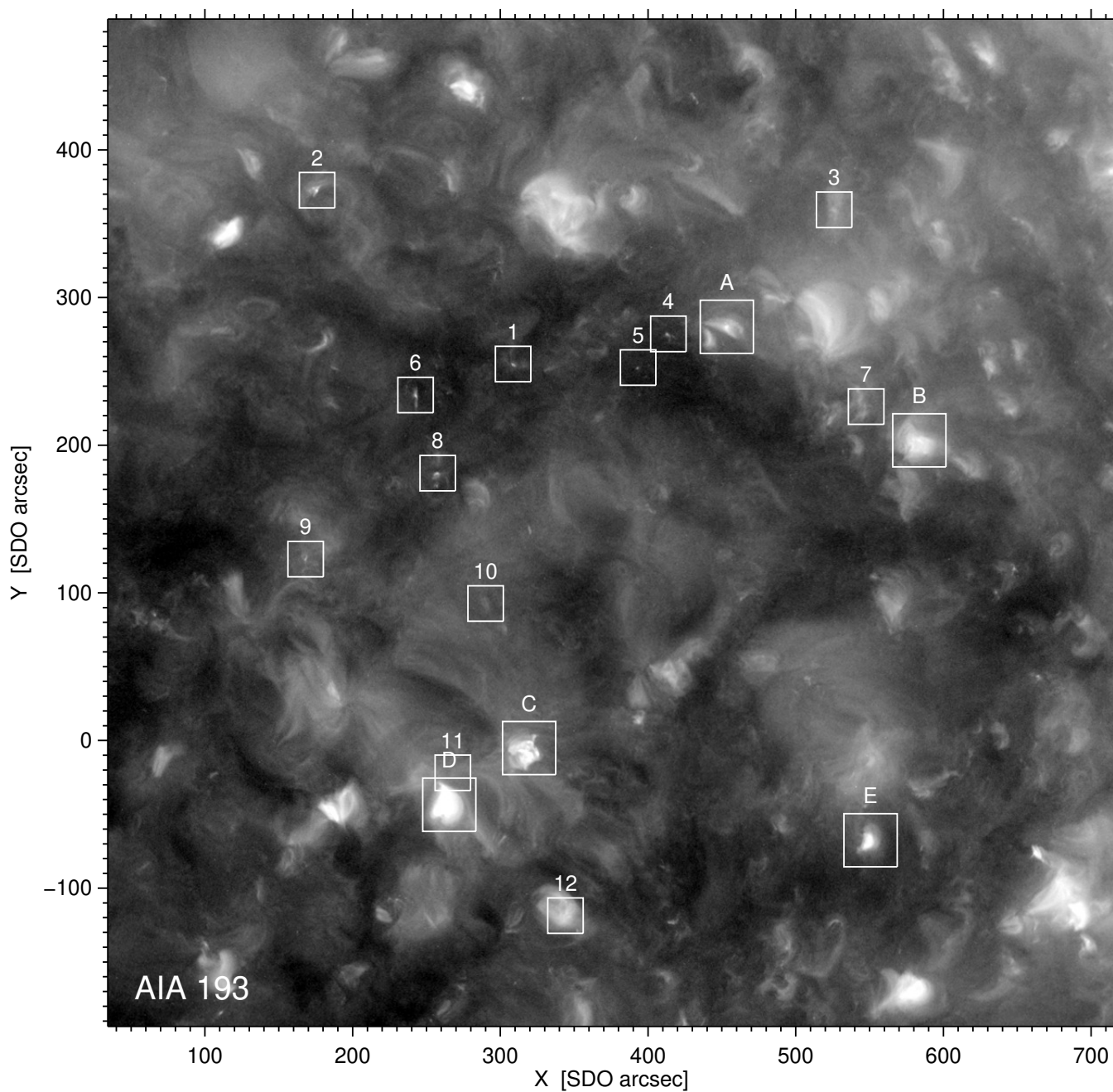


Fig. 67. The AIA 193 Å image at best-match time with superimposed ROI boxes for all campfire and brushfire cutouts.

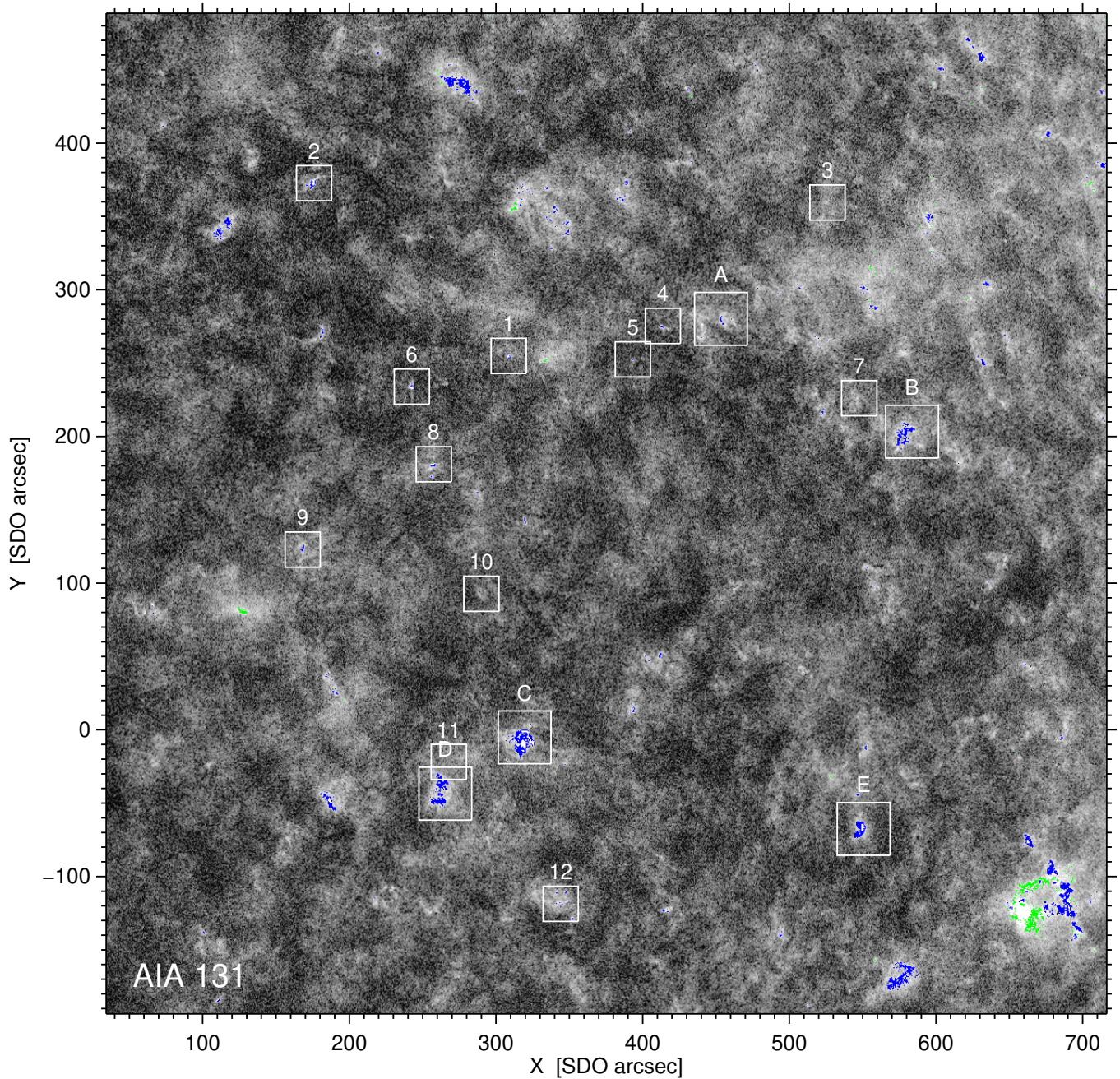


Fig. 68. The AIA 131 Å image at best-match time with superimposed ROI boxes for all campfire and brushfire cutouts. Green and blue pixels are those within the green and blue selection boxes in the righthand Strous diagram in [figure 74](#). Green pixels lie mostly in the bright patch in the lower-right corner; blue pixels lie in small bright features. Blinking with the preceding AIA 193 Å image shows that most are small brushfires, with bipolar MCs on the surface (blink one more back). However, most campfires also contain blue pixels. These colored pixel selections inspired the next figure.

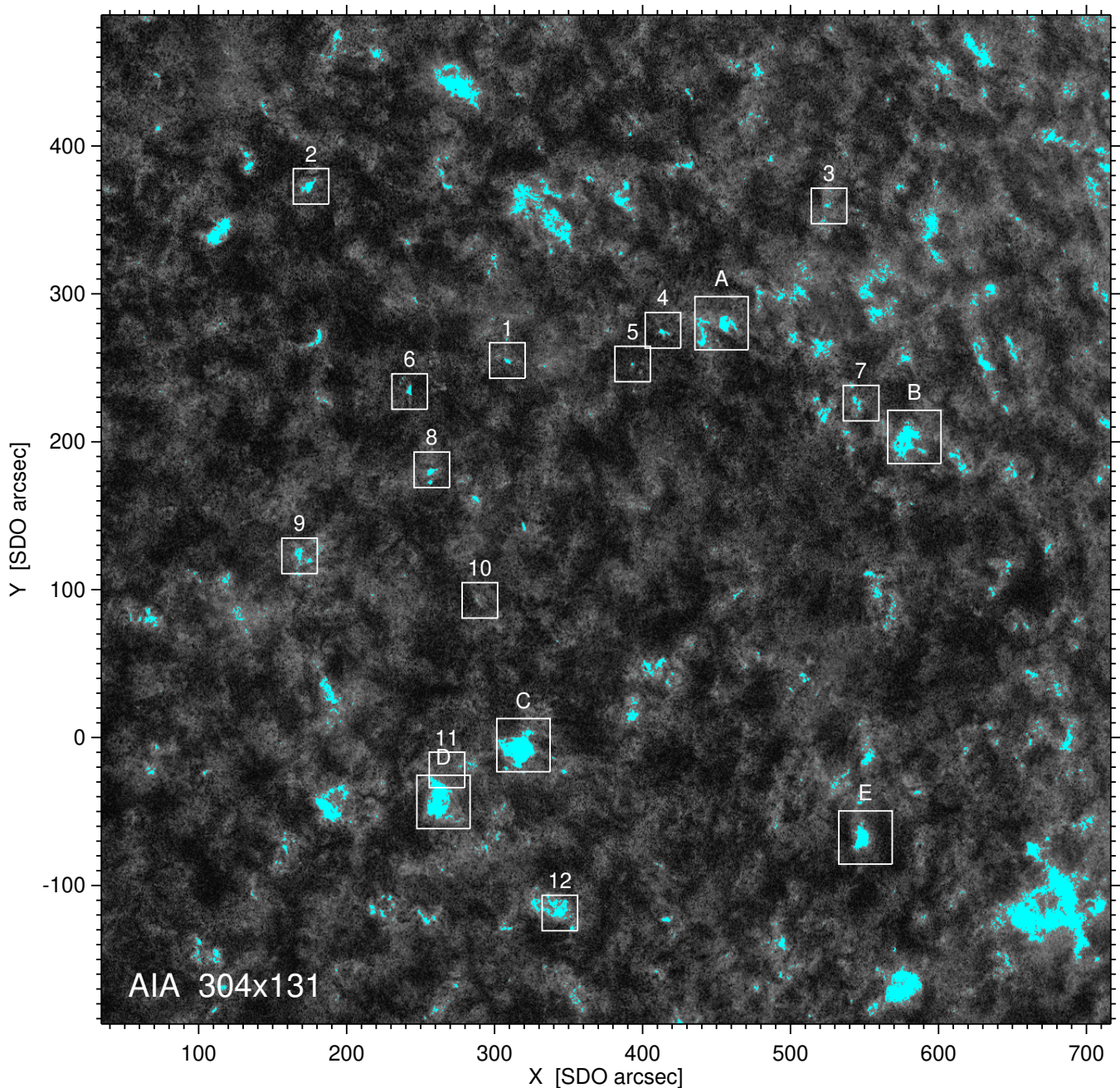


Fig. 69. SDO fire detector inspired by blinking AIA 304 and 131 Å in [figures 12](#) and [13](#), EBFAF detection ([appendix A](#)) and by the blue pixels in the preceding figure selected with the blue box in [figure 74](#). The scene is a construct: the best-match AIA 304 Å image in [figure 12](#) is multiplied by its 131 Å companion in [figure 13](#). The check plot in [figure 75](#) for this pair shows that their alignment is sufficiently precise. The brightest product pixels are colored cyan, chosen to convey EUV-hot fire temperature. The greyscale clip and color threshold are defined by the sequence-averaged quiet-network areas only, to avoid lopsiding by brighter active regions as present in [figure 30](#). The values are determined in `sdo_firelevel.pro` by iteratively removing brightest pixels in average and rms computation for the full sequence. The values used here are 10σ of left-over network above its average to clip active regions and 4.5σ threshold to color pixels cyan.

This stringent pixel-value selection appears useful as EUV fire detector. Spatial extent and temporal duration may then discriminate between small momentary campfires versus wider and more persistent brushfires.

The grey patches everywhere else represent dynamic chromosphere around quiet network. They are ubiquitously present with similar appearance in spreading around network MC concentrations, defining grey in this image well-suited as heated-chromosphere locator. It is hot since it is seen here and also as grey background in 171 Å ([figure 14](#)), AIA 221 Å and AIA 335 Å, but it is also darkly visible in $H\alpha$ (blink with [figure 11](#)). This dual visibility is discussed in [appendix B](#).

The darkest patches between the grey ones generally match dark features present in most other AIA EUVs and seen sharpest in 171 Å. However, in 193 Å ([figure 67](#) or [figure 15](#)) many seem covered by diffuse emission and others appear bright, for example the brushfire loop bundle to the right of ROI-A between ROI-3 and ROI-7 which only has footpoint pixels colored cyan here while most loops in this 193 Å-bright bundle appear dark in 131 Å ([figure 68](#) or [figure 13](#)) and in 171 Å ([figure 14](#)). Also this dual visibility is discussed in [appendix B](#).

Ten other fire detector scenes are shown as triple member in [figures 17–46](#). They separate well between chromospheric and coronal heating.

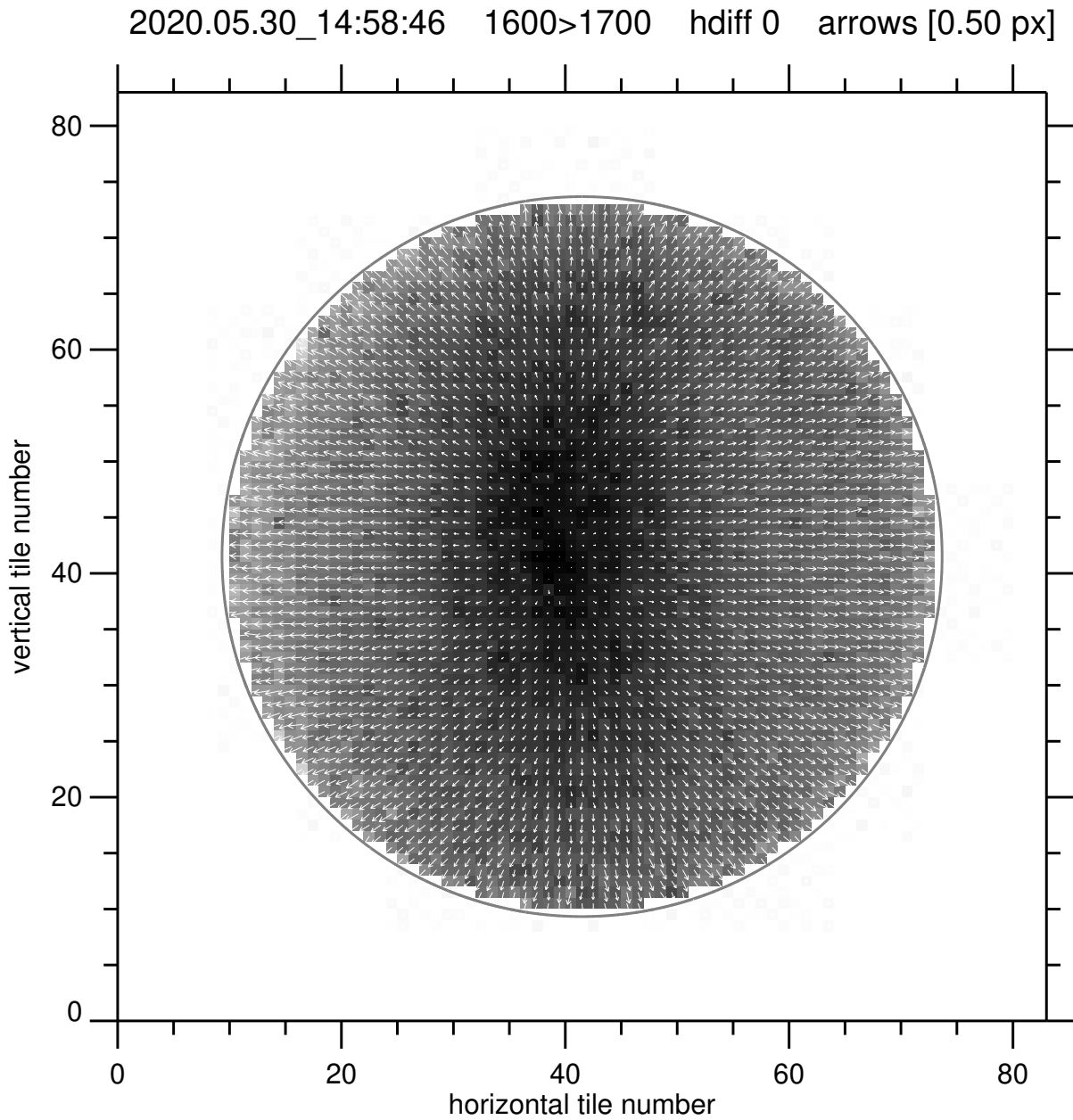


Fig. 70. Vector chart of apparent shifts of features in AIA 1700 Å to their location in AIA 1600 Å, measured by cross-correlation per subfield tile at the best-match time. The tiles are greyscaled to their vector length. Similar radial-expansion charts result throughout the SDO database. They represent my closest endeavor to cosmology.

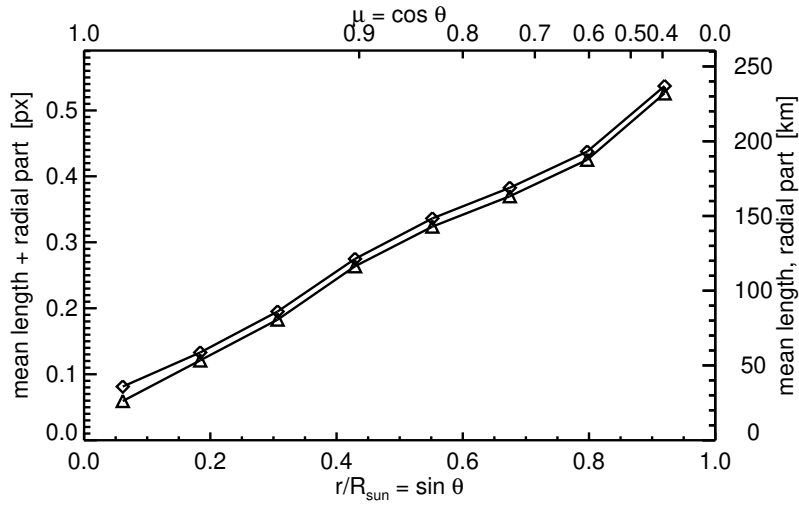


Fig. 71. Amplitudes of the shift vectors in [figure 70](#) averaged azimuthally along circular zones. The lower curve is the zonal average for the radial components. I attribute the final uptilt to C IV contribution in AIA 1600 Å and chose heightdiff = 220 km for [sdo_muckimagepair.pro](#) from this graph, in agreement with the measurement by [Alissandrakis \(2019\)](#). This value is not height-of-formation difference between samplings of vertical features as commonly thought, but a formal way of quantifying the apparent limbward displacements in [figure 70](#). Their actual cause is explained in [figure 73](#).

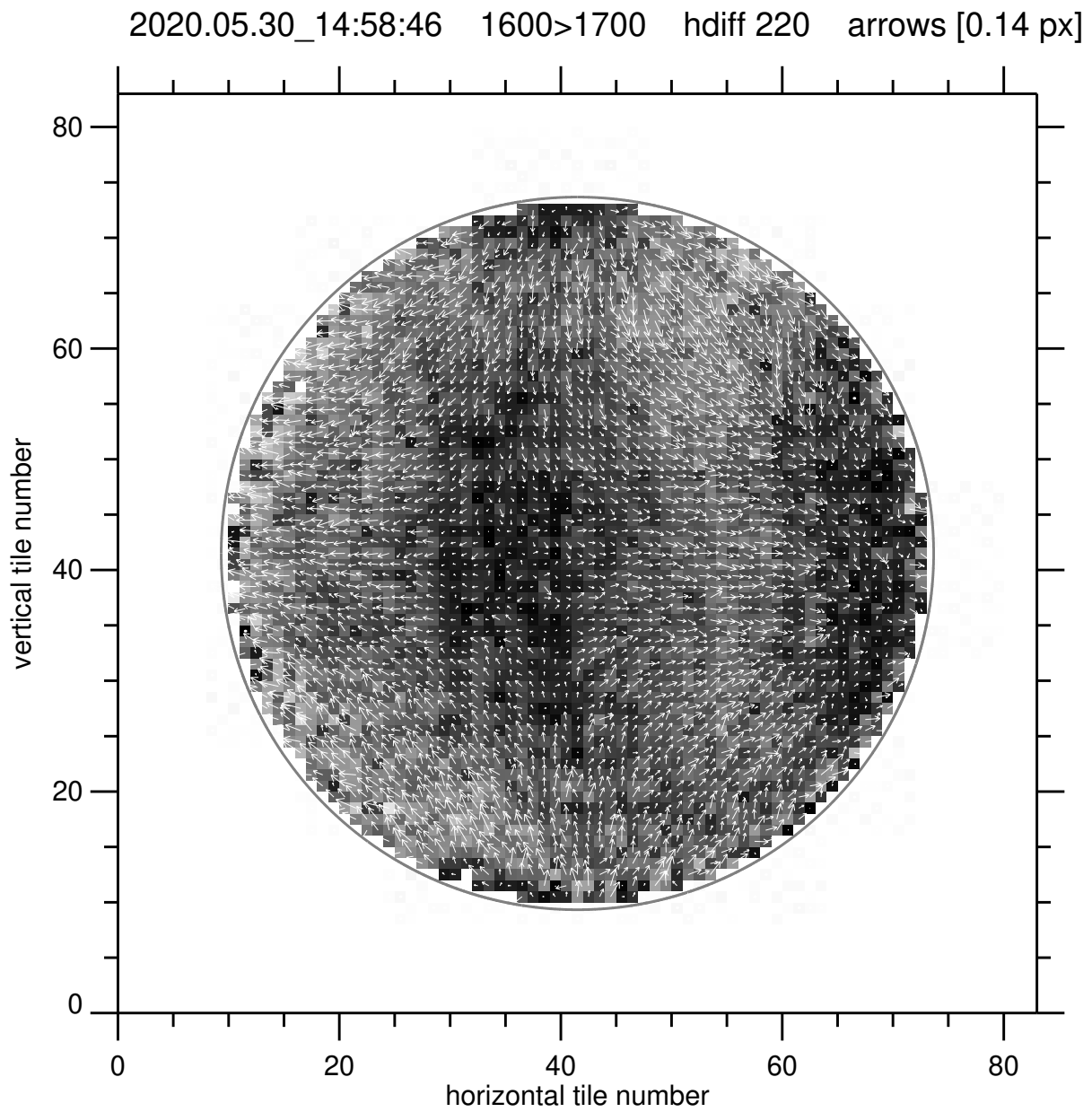


Fig. 72. Vector chart of apparent AIA 1700 to 1600 Å shifts after shift-back correction per tile using $\text{heightdiff} = 220$ km as formal limb value. The vector scale is expanded 3.6 times compared with [figure 70](#). I found closely similar residue patterns throughout the SDO database and do not understand it.

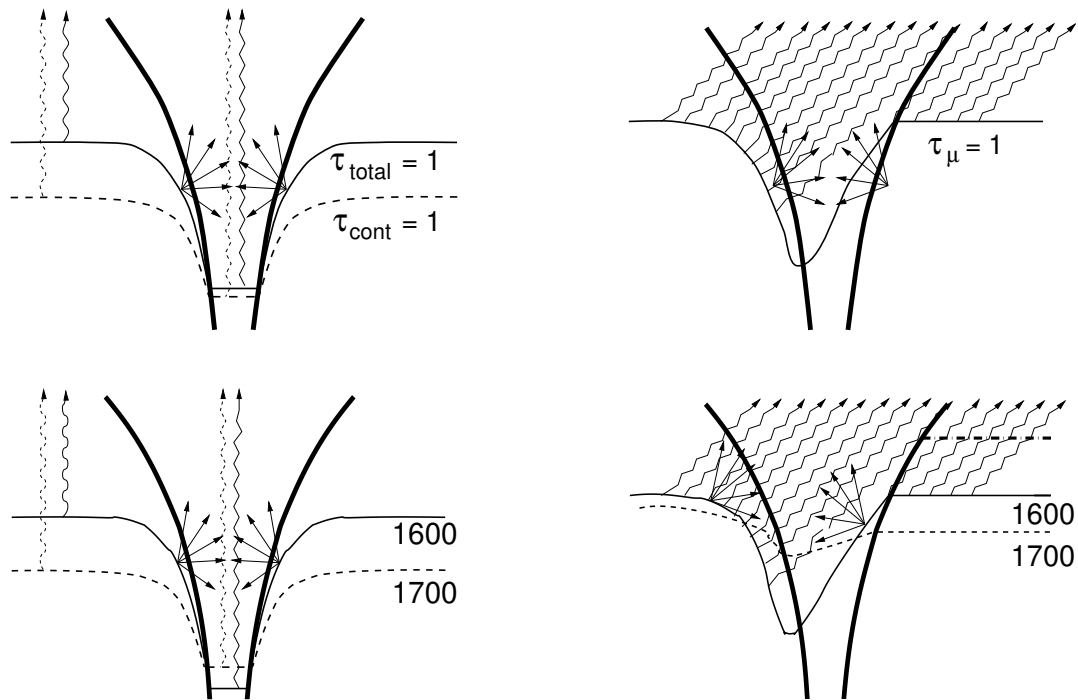


Fig. 73. *Top row:* ancient sketches to explain G-band brightening of “filigree grains” (here called magnetic concentrations = MCs, also known as flux tubes, fluxtubes, magnetic elements, magnetic bright points, intergranular bright points, network points, facular points, faculae, plage, flowers, pseudo-EBs, line gaps, pseudo-moustaches) copied from [Figure 7 \(pdf 8\)](#) in [Rutten \(1999\)](#).

Left: the radial view at disk center. This cartoon was first drawn by Kees Zwaan, based on his thesis ([Zwaan 1965](#)) and extract [Zwaan \(1967\)](#), much discussed at Sterrewacht Sonnenborgh (with Hans Rosenberg on this [1967 photograph](#)), and finally published as [Fig. 2 \(pdf 12\)](#) of [Zwaan \(1978\)](#). The Zwaan-style fluxtube is relatively empty because its magnetic pressure compensates part of the outside gas pressure in magnetostatic equilibrium ([Spruit 1976](#), Zwaan-inspired in contrast to this [creation diagram \(pdf 10\)](#)). Zwaan’s concept was observationally quantified by Sami Solanki and coworkers into Zürich wine-glass models (e.g., [Bünte et al. 1993](#)) using unresolved but sensitive multi-line spectropolarimetry initiated by [Stenflo \(1984\)](#) (see [Stenflo et al. 1984](#), [Solanki 1993](#)). The concept applies to gas-dominated atmospheric stratification with upward fluxtube flaring set by hydrostatic density decrease; for non-flaring field-dominated magnetostatic coronal loops see e.g., [Low \(1985\)](#), [November \(2004\)](#).

Visibility: top-down one views deeper into the fluxtube and receives larger brightness from its hotter hole-in-the-surface walls and bottom than from the field-free gas around it. The latter is sampled higher at lower temperature and also in a relatively dark intergranular lane (so that at non-subarcsec resolution these small brightenings and their surroundings blend into non-showing grey, [Title and Berger 1996](#)). In the G-band the low pressure causes extra dissociation of the CH molecules causing this Fraunhofer-named dark spectral feature, so that images selecting it show enhanced brightening compared to continuum wavelengths. Because this band is wide enough to accommodate interference-filter 10 Å bandpass it became very popular in short-exposure high-resolution photosphere imaging after [Muller \(1984\)](#) did so first. Thus, MC brightening comes from holes in the surface, deeper in the G-band, not necessarily from extra heating. The Ca II H & K wing study of [Sheminova et al. \(2005\)](#) found no MC heating throughout the photosphere, in conflict with the increasing temperature excess that is stipulated in plane-parallel plage models. MC heating becomes visible only higher up as chromospheric grain brightening in the Ca II H & K cores, mostly in the network but occasionally above internetwork MCs as the “persistent flasher” of [Brandt et al. \(1994\)](#).

Right: the same sketch served to explain why MCs become bright stalks (“faculae”, originally in white light) towards the limb. In slanted viewing the fluxtube foot is blocked to higher height by the surrounding denser gas (yet higher in the more opaque G band) whereas through the relatively empty fluxtube (yet emptier in G-band opacity) one views further into the hot = bright granule behind it than without a fluxtube crossing the line of sight. The apparent stalks represent lack of opacity along that.

Bottom row: the same sketch but modified to illustrate 1700–1600 Å MC brightness difference. Outside the tube the 1600 Å continuum opacity is larger but inside it is lower because the neutral metals ionize away (they are already minority stage) so that only the scattering Balmer continuum and some Rayleigh scattering remain.

Left: at 1600 Å the MCs are deeper holes than at 1700 Å and relatively brighter in byte-scaled top-down images (the outside scene is dominated by clapotispheric shocks that brighten less or darken). The same apparent deepening from neutral-metal ionization causes the classic “line gap” phenomenon in Fe I lines (e.g., [Stellmacher and Wiehr 1991](#)) which is seen best in Mn I lines ([Livingston and Wallace 1987](#)) from lack of microturbulent smearing in surrounding granulation ([Vitas et al. 2009](#)), and also similar MC “moustache” brightening (not EB but pseudo-EB, moustaches share that confusion) of the wings of the Na I D and Mg I b minority-stage lines (also [Stellmacher and Wiehr 1991](#)). For an SST/CRISP example of the latter see the MC near the center of the small field in [Figure 4 \(pdf 5\)](#) of [Rutten et al. \(2011\)](#). Its brightening enhancement in the wing of the majority-stage Ca II 8542 Å line in that figure comes from less collisional damping at smaller density reducing wing opacities. Such wing brightening by less-damping deepening is also seen in H α ([Leenaarts et al. 2006b](#)), H β and Ca II K ([Leenaarts et al. 2006a](#)). For recent SST examples see the first panels of [Fig. 1 \(pdf 2\)](#) of [Bose et al. \(2019\)](#); less-damping MC brightening is seen particularly well with the SST/CHROMIS wide-band filter at 3950 Å midway between Ca II H and K.

Right: towards the limb the MCs have higher-up dark foot blocking at 1600 Å by the more opaque surroundings, but the view through the tube deep into the hot granule behind starts deeper down at 1600 Å and extends further out in reaching $\tau_{\mu} = 1$ than at 1700 Å. The 1600 Å stalk therefore differs in morphology from the 1700 Å stalk, being brighter with apparent limbward shifts utterly evident in [figure 70](#).

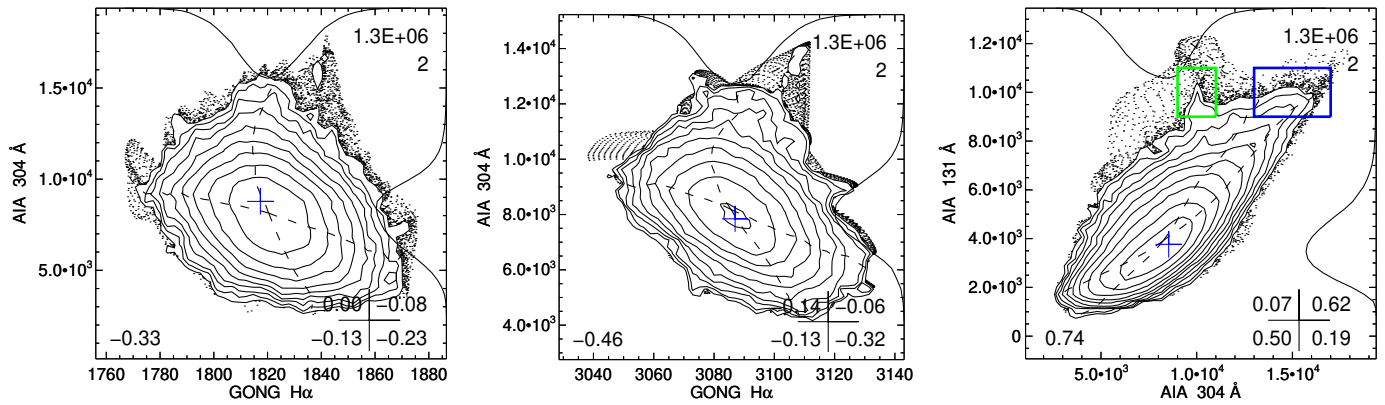


Fig. 74. Strous scatter diagrams. The format and inserted numbers are explained in Section 2 (pdf 2) of Rutten et al. (2019) with Figure 5 there (pdf 7) a relatively easy to interpret example. I make Strous diagrams with `scatcont.pro` based on Alfred de Wijn's version.

First panel: AIA 304 Å against GONG H α . For AIA 304 Å the temporal average of the 15-min sequence is used, for H α the non-reversed GONG image of figure 10 blurred over 30 pixels. The apparent overall correspondence of the grey patches in figures 11 and 12 is quantified as the significant downward tilt of the contour mountain of which the extended summit corresponds to grey in the images. Without correlation the mountain would be round with perpendicular first-moment curves. The rightward tilt of the upper end of the vertical first-moment curve suggests slightly brighter than normal grey for H α at brushfire sites.

Second panel: similar but now using sequence-averaged GONG H α . My success in co-aligning the single reversed H α image of figure 11 with the AIA 304 Å image of figure 12 made me develop `gong_sdo.pro` to co-align each of the best in a sequence of GONG H α images with simultaneous AIA 304 Å images. My motivation was that this may serve to co-align any H α observation with SDO by using GONG H α as intermediary, and also look-alike scenes such as ALMA images. Because the GONG images vary much in quality and considerably in scale, position and orientation automating such co-alignment is non-trivial, but I succeeded in obtaining a co-aligned GONG H α sequence for the present SDO downloads. The resulting Strous diagram is similar to the one at left but shows tighter relationships due to the now dual 15-min temporal and 30-px spatial averaging. This improvement fits my view of the chromosphere: heating to AIA 304 Å visibility occurs momentarily in the tips of spicules-II followed by darkening H α -core fibrils along their tracks, darkest at the track onsets so that the correlation concerns fine structures that are not precisely synchronous nor co-spatial but closely adjacent in space and time. Again, the tilted scatter mountain describes the grey chromospheric patches seen ubiquitously everywhere whereas the brightest 304 Å pixels describe fires. These appear only slightly brighter than average in H α so that low-resolution H α does not offer a viable means to locate them.

Third panel: AIA 131 against 304 Å, showing yet tighter spatial correlation for most-common grey pixels in figures 12 and 13. For both sequences the temporal means are used. I was curious about the small North-ward promontory on the North coast of this contour island. Inspection with `showex`, which can plot Strous diagrams live while blinking and also offers box-selection with image pixel coloring, made me add the green and blue selection boxes. Their pixels are colored correspondingly in figure 68. The blue ones appear to represent a viable fire locator and so inspired the multiplicative fire detector tested and described in figure 69. It serves as triple member in figures 17–46 to separate chromospheric and coronal heating.

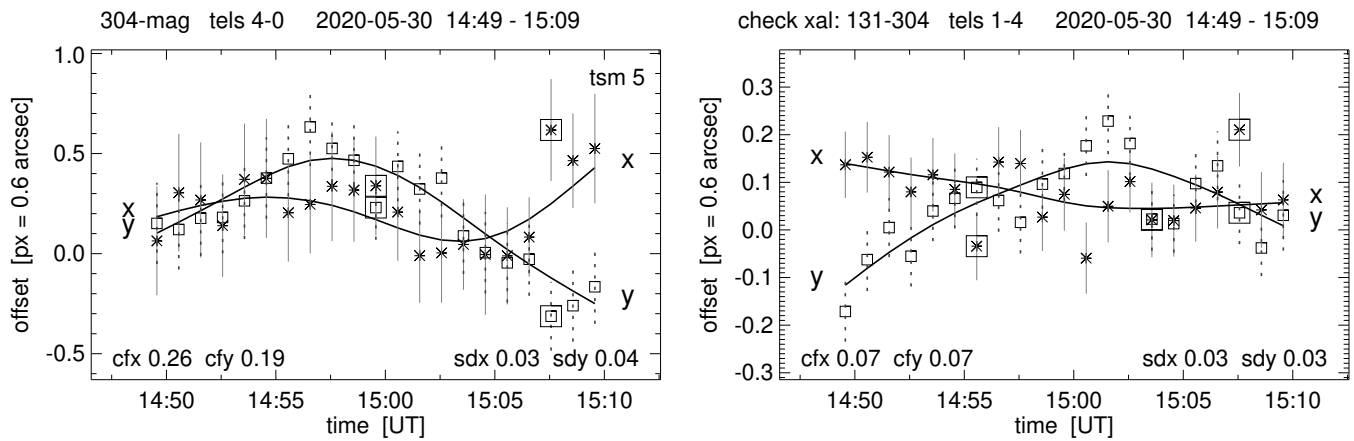


Fig. 75. *Left:* standard driftscenter plot from the SDO cross-alignment pipeline for the present SDO download, for the AIA 304 Å versus HMI magnetogram pair. These are made from low-cadence 700×700 arcsec² center cutouts by tiling into 30×30 arcsec² subfields as in [figures 70](#) and [72](#) and for every time step determining and averaging spatial offsets by cross-correlation per tile pair, after appropriate image “mucking” in [sdo_muckimagepair.pro](#) to make them appear more similar and using `heightdiff` correction, here with limb value 3600 km determined from zonal tile-shift averaging as in [figure 71](#). The error bars are 96% confidence limits for the next tile sample per time step. Their average values are specified at lower left. The boxed samples are outliers removed in iterative spline fitting. The resulting spline curves are stored and used to cross-align the actual target data. Their 1σ reliability is specified at the lower right. The pipeline produces such graphs for all pairs it employs. Generally they show time-varying drifts up to a few pixels between SDO diagnostics (more after eclipses or hiccups). Fixing the EUVs to HMI or UV is the hardest; currently this 304 Å – magnetogram pair is my default anchor choice.

Right: driftscenter check plot after all cross-alignments for the AIA 131 Å versus 304 Å pair, also made with [sdo_writepairspline.pro](#). The vertical axis range is smaller. Currently, the pipeline does not cross-align these directly but it roundabout cross-aligns 211 Å to 304 Å, 335 Å to 211 Å, 131 Å to 335 Å. There are more such chained cross-alignments, all anchored to the 304 Å to HMI magnetogram alignment at left, with their orders defined in [sdo_getsumsplineshift.pro](#) from `showex` scene comparisons to select best-matching pairs as well as appropriate mucking. Remaining errors add up statistically in such multi-step chains. Here, this check from cross-aligning the pipeline disk-center results, not its input, shows that the final errors for this pair are negligible, fully so at best-match time (14:58:46 UT). Before cross-alignment this `aia_prepped` input pair had consistent $(\Delta x, \Delta y) \approx (+0.3, -1.1)$ px offsets. Their reduction to 0.1 px ensures that the fire detector of [figure 69](#) multiplies appropriate pixel pairs.