nature portfolio

Peer Review File

Ubiquitous Kelvin-Helmholtz Instabilities in the Solar Photosphere

Corresponding Author: Dr David Kuridze

Any redactions in this file are there to maintain patient confidentiality, the confidentiality of unpublished data, or to remove third-party material.

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)
The manuscript reports on the detection of the Kelvin-Helmholtz Instability (KHI) in the solar photosphere. The KHI is a fundamental process crucial for modifying the properties of many physical phenomena. The manuscript uses observations from the most powerful solar telescope to show evidence of the KHI in the smallest astrophysical scales ever seen. It highlights the significance of KHI for the fragmentation of large magnetic structures and the subsequent generation of the small-scale magnetic elements that are ubiquitous in the photosphere. The detection of KHI at these small scales in the solar photosphere is somewhat unexpected, and was made with a relatively simple imaging setup. It highlights the discovery science that a facility like DKIST can make. The radiative MHD simulations reinforce the observational findings. The analysis of the observations and simulations is robust. Given the significance of the findings, I recommend the manuscript for publication in Nature.

Below, I list some comments and questions for the authors:

1. Line 67: A theoretical diffraction limit of 19 km is listed. This value is also used in some of the Figures (e.g. Extended Data Fig 2 d). Can you determine the actual spatial resolution of the observations from the imaging data? How much does it differ from the theoretical diffraction limit?

2. Line 79: The simulations start with a “seed” field. Is that field placed/distributed over the solar photosphere? My understanding, from the literature, is that in these simulations an average magnetic field is usually placed several Mm below the photosphere and is carried upwards by convection. Why was a “seed” field deemed more appropriate in this case?

3. Line 93: The statement needs a reference

4. Extended Data Figs 2d, 5d, 6d: The figures show that the peak of the distribution is above the theoretical telescope diffraction limit. They show that the vast majority of the wavelengths are resolved, as they are clearly above the diffraction limit. This implies that even with better spatial resolution, you will not detect smaller wavelengths. If that is the case, then that needs to be stated in the manuscript.

5. Line 249: What was the effective cadence post MFBD?

6. Line 446: Should be DKIST.

Referee #2

(Remarks to the Author)
This manuscript presents the discovery of previously unseen fine-scale structures and dynamics in regions of strong magnetic field in the solar atmosphere. The observations are of unprecedented spatial resolution and quality. They provide irrefutable evidence that there exist small-scale features in the solar atmosphere down to spatial scales of a few tens of

kilometers and demonstrate that a large-aperture solar telescope is capable of resolving these fundamental structures.

Besides presenting, for the first time, a uniquely detailed view of the magnetized solar atmosphere, which is a tremendous technological breakthrough in itself, the authors also present a compelling case for identifying these new structures and dynamics as a manifestation of Kelvin-Helmholtz instabilities. This interpretation is supported by state-of-the-art radiative MHD simulations. Furthermore, by employing an advanced radiative transfer code, the authors have produced synthetic observables from the simulations that include various aspects from the observations, such as spectral filter bandwidth, contribution from various spectral lines, and observation angle. The similarities between observations and synthetic observations are remarkable.

There is close agreement between observations and simulations, including the morphology, sizes of vortices and striations, dynamical evolution and time scales, and the characteristic spatial wavelength and growth rate of the KHI structures. This forms a solid basis for inferring properties of the solar atmosphere that are not directly probed by the observations, for example the to role of the KHI in forming the subsurface structure of magnetic elements that appear monolithic at the surface, and the transport of energy through the solar atmosphere.

These landmark observations will have high impact on solar physics and the planning of the next generation of large aperture optical solar telescopes, including the European Solar Telescope, the Chinese Giant Solar Telescope, and the National Solar Telescope in India.

I strongly recommend this paper for publication in Nature. I am sure that this work will have impact outside of solar physics and will attract attention from a wider audience.

The manuscript is well written and presents a clear and compelling case. The methods and assumptions are well documented. Figures and animations are clear.

I only have a few minor comments for consideration by the authors:

Line 186-187: A reference that should be added here is Scharmer et al. 2002 Nature 420, 151. Figure 3 showed for the first time different fine scale structures at the boundaries of magnetic elements in strong field regions in an active region. It appears to me that what was called "hairs" in these lower resolution SST observations are the striations discussed here (e.g. Extended Data Fig. 12).

Line 172-173: what is meant here with deeper photosphere? The layer around tau=1 or the region below the visible surface? The depth range considered in this paragraph is z +100 to -400 km, please clarify to avoid confusion.

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Caption Fig. 2: "The arrows indicate..." : arrows are only shown in panel (e)

Caption Fig. 4, line 428: "vertical cut" should be horizontal cut

Figure 4 panels in a: please consider to change the style of the "invisible" axes in the box: the bottom y-axis (0, y, -787.2) and the z-axis in the back (796.8, 796.8, z). This would make it easier understand the viewing direction.

Line 446 typo DKSIT -> DKIST
Line 450 blue line in panel b -> panel c

Extended Data Fig. 8, panel d: how is the red line defined?

Referee #3

(Remarks to the Author)
This is a discovery solar paper. It highlights the development of the Kelvin Helmholtz instability (KHI) at very small scales near the Sun's surface. More precisely, it shows that the KHI occurs right at the edges of magnetic flux concentrations located between granules, and that the shear layers are formed by surface convective motions. In addition, the paper provides quantitative measurements for the key physical parameters of the KHI. The discovery is made possible thanks to the spectacular observational capabilities of the American DKIST located in Hawaii, supplemented with a magneto convection simulation with the MURaM code, both benefiting from ultra high spatial resolution, and the authors' analyses for the KHI. The KHI parameters are measured with great care both in the model and the observations, they are reframed in the context of the proper analytical theory, and they are compared and found to be consistent with one another. The results are far reaching not only regarding the nature of magneto convection, but also for their consequences in the heating of the Sun's atmosphere. Overall this is a landmark paper that certainly ought to be published in Nature.

I still have a few questions which I would argue the papers would benefit from if the authors would address them before publication.

1. The nature of striations :

One could argue that the nature of striations is a bit overlooked in the manuscript and could be specified. The paper does make a compelling case that the "KH instability [...] corrugates the boundaries of the MFCs", but it also raises some questions. Ref [29] Carlsson et al (2004) has shown that such striations are mostly visible at large inclination angles, i.e. for small mu. Ref [30] Kuridze et al (2025) observed at mu=0.85, hence at 30 degree angle which relatively inclined too. But the present Fig. 2 and Supplementary Video S3 actually reveal that all striations are visible even viewed from the top, at mu=1. This may be surprising. Also, the paper reads "striations seen in filtergrams are associated with spatial and temporal modulations of the photospheric magnetic field". However each Bz related Figure and video in the paper show no striation whatsoever. Would striations appear in horizontal field maps ? This (apparent?) contradiction probably requires some illustration, and maybe some rephrasing of the results from Ref [30], if it still holds : "the striation observed in the filtergrams is associated with spatial variations in photospheric magnetic flux concentrations, which cause shifts in the geometrical height where the emergent intensity forms". Given the prevalence of these striations in the observations and the simulation, some clarification regarding their nature would be welcome.

2. Regarding the simulation :

2.1. Extended Data Fig. 10 provides a glimpse of the coverage of the simulation through the convection zone and the overlying solar atmosphere. But explicit information about this is missing from the Methods sections. A few lines about this aspect of the setup be welcome there. Also a brief discussion about the role of this overlying convectively stable atmosphere in the formation of the flows that trigger the KHI would also be welcome : in other words, can these KH rolls exist in purely convective regions ?

2.2. The justification for the use of an "enhanced magnetogram" should be strengthened. On one hand, one can read that the "KHI develops [...] surrounding vertically oriented MFCs", and that such vertical B "provides no stabilization". Indeed this is expected since vertical B cannot develop any curvature to fight against the KHI. And this is good, as one can conclude that enhancing the magnetogram should not much change the results about the KHI. But on the other hand, one reads that we "need to compensate the field dispersal that happens due to granular motions". This can look surprising, since one may argue that any vertical B would be advected in the same way, regardless of its magnitude, just like it plays no role in the KHI. So the paper should explain more why this enhancement was needed at all ? And finally, why was this particular "form" chosen ?

2.3. The highest resolution of the simulation is 3.2 km whereas the widths _d_ of the shear layers from which KHI originates range between 10 to 15 km, hence about 3 to 5 times the resolution. How does this compare with the stencil ? By which relative magnitude is _d_ governed by the physics (e.g. pressure balance) and by the numerics (e.g. diffusion) ? Given Extended Data Fig. 7 panel c, and Supplementary Fig. 6, how sensitive would this issue be ?

3. Adjusting Figures :

3.1. Several of the first figures that show simulation results are presumably plotted along the Z axis, i.e. top views, i.e. mu=1 : it would be desirable to specify it in the captions.

3.2. Plotting the vorticity (to highlight sources of the KHI) and the plasma beta (since it is refereed to in the text) in the vertical cuts would be useful in Extended Data Fig. 10, hence making it a 6-panel figure.

4. Other points to be addressed :

4.1. The origin of the shear flows is taken for granted. While it is (or may seem) obvious for convection experts, one or two sentences explaining it (e.g. following lies 102-103) could be useful for non-specialists.

4.2. The consequences of ubiquitous surface vortices in solar (and stellar) atmospheric heating could be supplemented by some sentences and references (e.g. around lines 206 and/or 214). Indeed numerous vortices most likely provide a source of small-scale but widespread flux braiding, and therefore of many overlooked small-scales in the Sun's atmosphere, that will provide electric current sheets all along the field lines anchored at the Sun's surface, independently of turbulence of vortex merging. Since this flux braiding model is one of the main ideas for coronal heating, and since it is always looking for observed sources of braiding motions, it is arguable that it should be referred to here.

4.3. The link with Parker's 1979 reference is not so obvious. Firstly the way the present paper quotes it seems to present a contradiction. On one hand, the Summary states that the "KHI [...] supports the theory of disjoint magnetic flux concentrations [...] that _combine to form_ strong monolithic flux regions [...] as proposed by E. Parker". On the other hand the Article reads "KHI at the magnetic boundaries leads to a _fragmentation and splits_ the monolithic magnetic element [...] into individual strands below it, was originally proposed by Parker". Secondly, Parker's 1979 series addressed many physics questions, the main ideas being : (i) propagating Alfvén waves are responsible for the fragmentation below sunspots ; (ii) large-scale convective converging flows stabilize the sunspot structure. But to this reviewer's knowledge, such Alfvén waves are not seen in modern simulations. Also in the present paper, it is KHI that leads to fragmentation, and it occurs only on the edge of the flux concentrations, and all at once at every depth, more and more efficient with depth as very well explained in the present paper. Finally Cheung, Rempel, Title & Schüssler (2010, ApJ 720, 233) have actually shown the sunspot stability to be ensured by their deep magnetic roots, not by convective flows. And the same authors (like a few others) have obtained fragmented sunspots, without Alfvén waves, or KHI. In a nutshell, unless the authors provide compelling arguments, I would argue that the present KHI discovery hardly relates to Parker's 1979 ideas, that it does not need to, and that its consequences are actually much farther reaching, presumably mostly atmospheric / coronal heating.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)
I have reviewed the revised version, and I am satisfied that the authors have addressed the comments and questions raised by the reviewers. This scientific discovery has far-reaching implications beyond solar physics and is ideally suited for Nature.

Referee #2

(Remarks to the Author)
The response and the changes to the manuscript are satisfactory. The revision has further strengthened the manuscript. I strongly recommend publication in Nature.

Referee #3

(Remarks to the Author)
The authors' responses to all my comments are very satisfactory, therefore I am glad to recommend this impressive paper to be published in Nature.

Title: “Ubiquitous Kelvin-Helmholtz Instabilities in the Solar Photosphere”

Submitted to Nature 2026-03-07645

Dear Dr. Urmila Chadayammuri,

We thank you for sending us the formatting guidelines. We have revised the manuscript accordingly and implemented the required formatting changes.

Summary of formatting changes:

1. We shortened the title.
2. We moved three figures from the Methods section to the Supplementary Material to meet the suggested limit of 10 figures in the Methods section.
3. We formatted axes and labels according to the formatting guidelines.

Please let us know if any further adjustments are needed.

Reply to the referee's comments:

We would like to express our gratitude to all the referees for their appreciation and appraisal of our work and for their helpful reports that have improved the paper. We have taken the referees’ comments into account and revised the manuscript accordingly. Below we provide a detailed response. In the manuscript the changes are indicated by black bold face text.

Referee expertise:

Referee #1: Observational signatures of chromospheric and coronal heating

Referee #2: High-resolution solar observations

Referee #3: Theory and MHD simulations of solar eruptions

Referees' comments:

Referee #1 (Remarks to the Author):

The manuscript reports on the detection of the Kelvin-Helmholtz Instability (KHI) in the solar photosphere. The KHI is a fundamental process crucial for modifying the properties of many physical phenomena. The manuscript uses observations from the most powerful solar telescope to show evidence of the KHI in the smallest astrophysical scales ever seen. It highlights the significance of KHI for the fragmentation of large magnetic structures and the subsequent generation of the small-scale magnetic elements that are ubiquitous in the photosphere. The detection of KHI at these small scales in the solar photosphere is somewhat unexpected, and was made with a relatively simple imaging setup. It highlights the discovery science that a facility like DKIST can make. The radiative MHD simulations reinforce the observational findings. The analysis of the observations and simulations is robust. Given the significance of the findings, I recommend the manuscript for publication in Nature.

Below, I list some comments and questions for the authors:

Reviewer comment: 1. Line 67: A theoretical diffraction limit of 19 km is listed. This value is also used in some of the Figures (e.g. Extended Data Fig 2 d). Can you determine the actual spatial resolution of the observations from the imaging data? How much does it differ from the theoretical diffraction limit?

Our reply: We estimate a spatial resolution close to the diffraction limit based on the size of the smallest resolved structures observed in the reconstructed data. In particular, we selected the narrowest dark striations and measured the FWHM of Gaussian fits to the intensity profiles along cross-sections of individual structures. The Figure.1 below shows a few examples of such measurements, confirming that structures with widths close to the Rayleigh diffraction limit of the telescope (~19 km) are resolved in the images. This finding is consistent with the spatial Fourier noise filter settings used in the reconstruction algorithm.

A corresponding comment has been added in the *revised* version (**lines 263-265**).

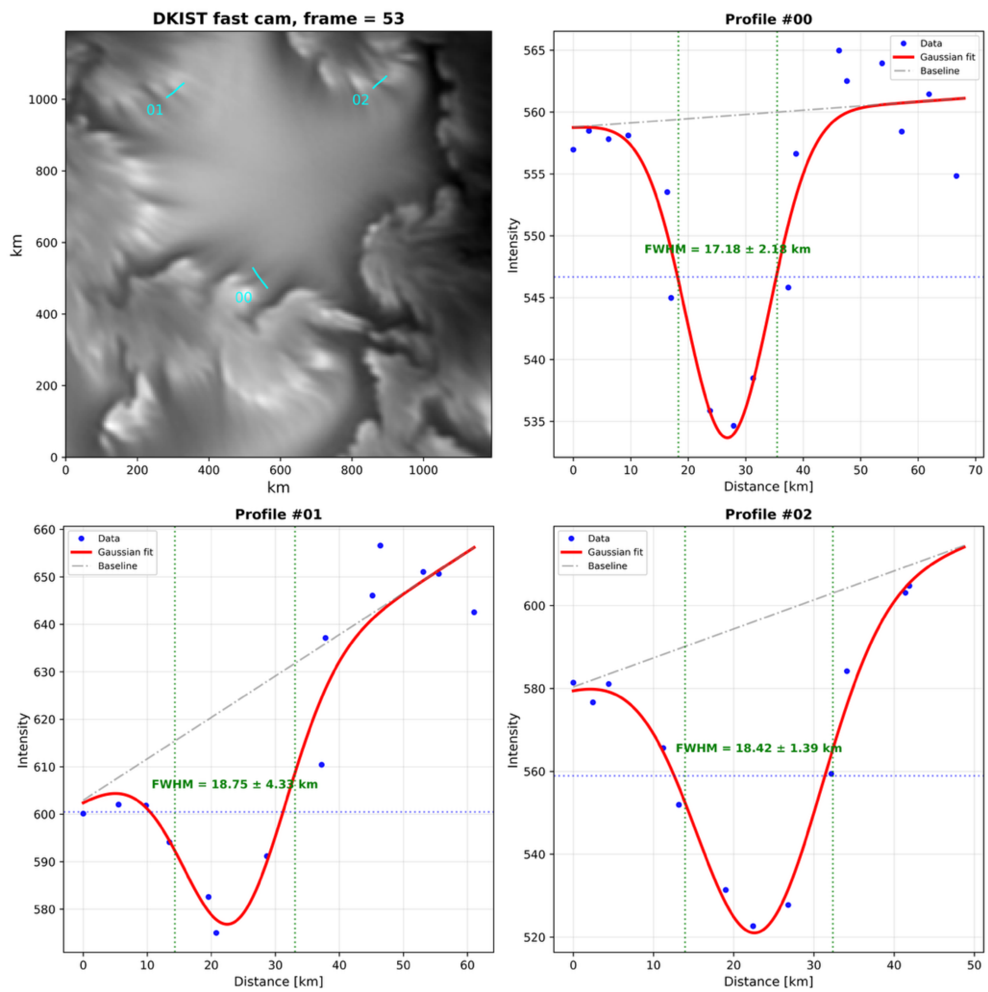

Figure.1*: Intensity profiles along the crosscuts of dark striae marked with cyan dashes in the top-left 416nm image. Gaussian fits of the individual profiles are overplotted in red.*

Reviewer comment: 2. Line 79: The simulations start with a “seed” field. Is that field placed/distributed over the solar photosphere? My understanding, from the literature, is that in these simulations an average magnetic field is usually placed several Mm below the photosphere and is carried upwards by convection. Why was a “seed” field deemed more appropriate in this case?

Our reply: With “seed” field we mean the initial magnetic field configuration, which is a vertical field corresponding to the vertical component of the field measured by HMI for the observed patch. Starting with a vertical field is standard practice when simulating plage or other magnetic concentrations outside sunspots. We recognize that ‘initial field’ would be the much better term here. We have changed the text to make this clearer on **line 80-81 (**and related: **lines 294-296)** of the *revised* manuscript.

Reviewer comment: 3. Line 93: The statement needs a reference

Our reply: This statement is based on numerical simulations performed by M.R., although the corresponding results are not shown in the manuscript. To clarify this point, we have added an explicit statement in **line 93-95** in the *revised* manuscript.

Reviewer comment: 4. Extended Data Figs 2d, 5d, 6d: The figures show that the peak of the distribution is above the theoretical telescope diffraction limit. They show that the vast majority of the wavelengths are resolved, as they are clearly above the diffraction limit. This implies that even with better spatial resolution, you will not detect smaller wavelengths. If that is the case, then that needs to be stated in the manuscript.

Our reply: We have avoided stating that smaller KHI wavelengths will not be detected with a larger telescope, even though the histograms peak at ~65 km wavelength for our observations. We do not believe to have conclusive evidence for such a definitive statement. For example, the histograms for observations and simulations do not exhibit exactly the same shape. Investigation of numerical simulations with higher spatial sampling is unfortunately out of the scope of this work, because increasing the spatial resolution in the numerical simulations is too expensive (relevant here: lines 307-311 in the *revised* manuscript).

We have added the corresponding discussion and comments to the Methods section in the *revised* manuscript **(lines 449-452**).

Reviewer comment: 5. Line 249: What was the effective cadence post MFBD?

Our reply: After reconstruction, the effective cadence of the FastCam data was 2.7 s. A corresponding comment has been added in the *revised* version (**lines 263-265**).

Reviewer comment: 6. Line 446: Should be DKIST.

Our reply: We have corrected it in the *revised* version (**line 501**).

Referee #2 (Remarks to the Author):

This manuscript presents the discovery of previously unseen fine-scale structures and dynamics in regions of strong magnetic field in the solar atmosphere. The observations are of unprecedented spatial resolution and quality. They provide irrefutable evidence that there exist small-scale features in the solar atmosphere down to spatial scales of a few tens of kilometers and demonstrate that a large-aperture solar telescope is capable of resolving these fundamental structures.

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These landmark observations will have high impact on solar physics and the planning of the next generation of large aperture optical solar telescopes, including the European Solar Telescope, the Chinese Giant Solar Telescope, and the National Solar Telescope in India.

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Our reply: We thank the reviewer for pointing this out. Scharmer et al. 2002 is indeed one of the pioneering works in which striations were detected using high-resolution observations. The reference has been added to the *revised* manuscript (**lines 192, 742-744**).

Reviewer comment: Line 172-173: what is meant here with deeper photosphere? The layer around tau=1 or the region below the visible surface? The depth range considered in this paragraph is z +100 to -400 km, please clarify to avoid confusion.

Our reply: Thank you for pointing out this! By “deeper photosphere”, we mean layers below the visible surface (below tau=1 or z=0). The reviewer is correct. As tau=1 layer marks the base of the photosphere, it is not strictly accurate to refer to the layers below it as photospheric. We have corrected and clarified this in the *revised* manuscript (**line 176**).

Reviewer comment: Line 228-229: it is not relevant to provide the pointing X,Y coordinates down to 3 decimal precision.

Our reply: We thank the referee for this suggestion. The pointing X,Y coordinates have been reformatted in the *revised* manuscript (**lines 240-241**), and the unnecessary decimal precision has been removed.

Reviewer comment: Extended data Fig.13 equation (1) : there seem to be some errors: first line, U_0 should be -U_0? Second line, first d/2 should be -d/2? Third line, -U_0 should be U_0?

Our reply: We thank the referee for carefully checking the equations. The referee is correct: the signs of U and d/2 in the equation were not consistent with the figure. We have corrected them in the *revised* manuscript (as we moved three figures from the Methods section to the Supplementary Information, this is now Extended Data Fig. 10 in the *revised* manuscript; **line 364**). In Extended data Fig.10, we have also added subscripts to rho (rho_1 and rho_2) to make the notation consistent with Table 1, where rho_1 and rho_2 are used.

Reviewer comment: Caption Fig. 2: "The arrows indicate..." : arrows are only shown in panel (e)

Our reply: We have corrected this in the *revised* manuscript (**lines 468-469**).

Reviewer comment: Caption Fig. 4, line 428: "vertical cut" should be horizontal cut

Our reply: We agree and have adjusted the Figure caption in the revised manuscript accordingly (**line 483**).

Reviewer comment: Figure 4 panels in a: please consider to change the style of the "invisible" axes in the box: the bottom y-axis (0, y, -787.2) and the z-axis in the back (796.8, 796.8, z). This would make it easier understand the viewing direction.

Our reply: We have adjusted Figure 4 to change the ‘invisible’ axes to be in light gray in the revised manuscript (**line 479**).

Reviewer comment: Line 446 typo DKSIT -> DKIST

Our reply: We have corrected it in the *revised* version (**line 501**)

Reviewer comment: Line 450 blue line in panel b -> panel c

Our reply: We have corrected it in the *revised* version **(lines 504-505)**.

Reviewer comment: Extended Data Fig. 8, panel d: how is the red line defined?

Our reply: The red curve in panel d marks the measured KHI amplitude at that particular time step (as we moved three figures from the Methods section to the Supplementary Information, this is now Extended Data Fig. 7 in the *revised* manuscript). The figure caption has been amended for clarification in the *revised* manuscript (line 538-539).

Referee #3 (Remarks to the Author):

This is a discovery solar paper. It highlights the development of the Kelvin Helmholtz instability (KHI) at very small scales near the Sun's surface. More precisely, it shows that the KHI occurs right at the edges of magnetic flux concentrations located between granules, and that the shear layers are formed by surface convective motions. In addition, the paper provides quantitative measurements for the key physical parameters of the KHI. The discovery is made possible thanks to the spectacular observational capabilities of the American DKIST located in Hawaii, supplemented with a magneto convection simulation with the MURaM code, both benefiting from ultra high spatial resolution, and the authors' analyses for the KHI. The KHI parameters are measured with great care both in the model and the observations, they are reframed in the context of the proper analytical theory, and they are compared and found to be consistent with one another. The results are far reaching not only regarding the nature of magneto convection, but also for their consequences in the heating of the Sun's atmosphere. Overall this is a landmark paper that certainly ought to be published in Nature.

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Reviewer comment: 1. The nature of striations :

One could argue that the nature of striations is a bit overlooked in the manuscript and could be specified. The paper does make a compelling case that the "KH instability [...] corrugates the boundaries of the MFCs", but it also raises some questions. Ref [29] Carlsson et al (2004) has shown that such striations are mostly visible at large inclination angles, i.e. for small mu. Ref [30] Kuridze et al (2025) observed at mu=0.85, hence at 30 degree angle which relatively inclined too. But the present Fig. 2 and Supplementary Video S3 actually reveal that all striations are visible even viewed from the top, at mu=1. This may be surprising. Also, the paper reads "striations seen in filtergrams are associated with spatial and temporal modulations of the photospheric magnetic field". However each Bz related Figure and video in the paper show no striation whatsoever. Would striations appear in horizontal field maps ? This (apparent?) contradiction probably requires some illustration, and maybe some rephrasing of the results from Ref [30], if it still holds : "the striation observed in the filtergrams is associated with spatial variations in photospheric magnetic flux concentrations, which cause shifts in the geometrical height where the emergent intensity forms". Given the prevalence of these striations in the observations and the simulation, some clarification regarding their nature would be welcome.

Our reply: We thank the referee for pointing this out. The formation of striations at the disk center (DC) is not discussed in the paper, and we agree that this phenomenon deserves further explanation, especially since, as noted by the reviewer, it has been studied and observed primarily at large inclination angles.

Extended Data Fig.9k confirms that the striations seen in the filtergrams at DC are an opacity effect. To investigate the origin of these opacity variations, we examined the correlation between the relevant physical parameters. Fig.2 below shows the emergent intensity, B_z, and density at a height of z=128 km, sampled along the dashed line crossing the striations. The figure demonstrates that the striations in the emergent intensity are closely correlated with variations in B_z and anti-correlated with density in the upper layers. This suggests that the deformation of the magnetic boundary at the surface due to the KHI, modulates the photospheric magnetic field strength in the upper layers, which in turn causes variations in density and opacity along the line of sight, ultimately leading to the formation of striations in the emergent intensity.

As striations are radiative transfer effects arising from opacity-height integration, we do not observe narrow, extended fine structures in the single-height magnetic field maps. The location where the cyan line is drawn in Fig.2 (see below) lies outside the magnetic flux region at the average $\tau = 1$ height. However, KHI produces magnetic field variations in the higher layers, causing the $\tau = 1$ surface to form at different heights. This is the same physical mechanism responsible for the formation of striations observed at inclined viewing angles. The inclined viewing geometry makes the striations appear longer, more extended toward the limb, and therefore easier to detect. However, sufficiently high spatial resolution should also allow striations to be detected at disk center.

A corresponding comment **(lines 342-353)** and a new figure (Supplementary Fig. 9) has been added to the *revised* manuscript in the Methods section.

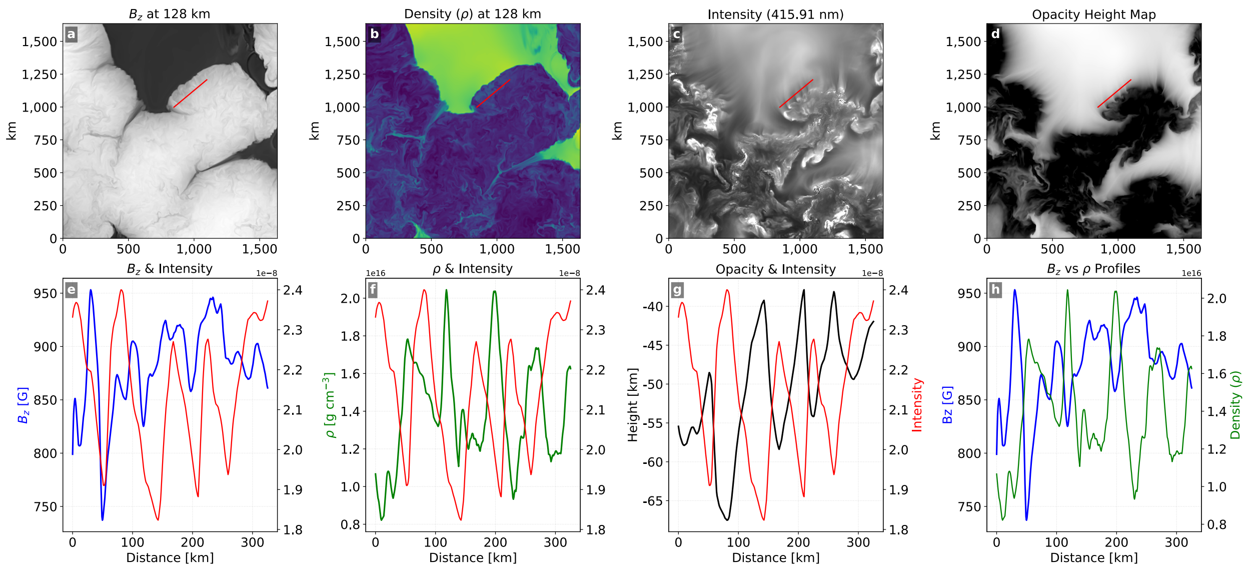

Fig.2: *Top: maps of the vertical magnetic flux density, B_z and density from the MURaM snapshot at the height z=128 km, emergent intensity and the map of the geometrical height where tau=1 at 415.9nm. Bottom: Profiles of these parameters along the cyan dashed line crossing the dark striae.*

Reviewer comment: 2. Regarding the simulation:

2.1. Extended Data Fig. 10 provides a glimpse of the coverage of the simulation through the convection zone and the overlying solar atmosphere. But explicit information about this is missing from the Methods sections. A few lines about this aspect of the setup be welcome there. Also a brief discussion about the role of this overlying convectively stable atmosphere in the formation of the flows that trigger the KHI would also be welcome : in other words, can these KH rolls exist in purely convective regions ?

Our reply: We have added a further clarifying statement in the Method section about how the numerical simulation extends through into the convection zone and the overlying atmosphere. Without having the overlying stable atmosphere, a solar-like setup with granulation driven by radiative losses cannot be achieved in the numerical simulation. A realistic photosphere is essential to make the connection between numerical models and observations. While KHI may exist in purely connective and artificially forced convection, it would likely not be observable. We have adjusted the *revised* manuscript accordingly (**lines 284-288**).

Reviewer comment: 2.2. The justification for the use of an "enhanced magnetogram" should be strengthened. On one hand, one can read that the "KHI develops [...] surrounding vertically oriented MFCs", and that such vertical B "provides no stabilization". Indeed this is expected since vertical B cannot develop any curvature to fight against the KHI. And this is good, as one can conclude that enhancing the magnetogram should not much change the results about the KHI. But on the other hand, one reads that we "need to compensate the field dispersal that happens due to granular motions". This can look surprising, since one may argue that any vertical B would be advected in the same way, regardless of its magnitude, just like it plays no role in the KHI. So the paper should explain more why this enhancement was needed at all ? And finally, why was this particular "form" chosen ?

Our reply: We thank the referee for the insightful comment. Indeed, it is the net flux imbalance – that was unchanged by the enhancement – that matters for the magneto convection. As the simulation covered more than 1.8h (or approximately 20 granular lifetimes) prior to the sequence that was analyzed in this work, the individual flux concentrations are no longer impacted by the initial state. Only the larger scale distribution is affected. The enhanced magnetogram was primarily used to create a setup that looks more closely like the observed distribution, and was not at all needed for studying the KHI. We have clarified the *revised* manuscript accordingly (**lines 297-302**).

Reviewer comment: 2.3. The highest resolution of the simulation is 3.2 km whereas the widths _d_ of the shear layers from which KHI originates range between 10 to 15 km, hence about 3 to 5 times the resolution. How does this compare with the stencil ? By which relative magnitude is _d_ governed by the physics (e.g. pressure balance) and by the numerics (e.g. diffusion) ? Given Extended Data Fig. 7 panel c, and Supplementary Fig. 6, how sensitive would this issue be ?

Our reply: The stencil is 5 grid cells. While simulations with smaller grid spacings do show smaller scale structures (we did experiments down to 800m grid spacing in a domain with reduced extent), numerical diffusivity becomes also smaller than Spitzer resistivity (see **lines 306-310** in the *revised* manuscript).

Reviewer comment: 3. Adjusting Figures :

3.1. Several of the first figures that show simulation results are presumably plotted along the Z axis, i.e. top views, i.e. mu=1 : it would be desirable to specify it in the captions.

Our reply: We have now indicated where the images were synthesized at the disk center in the *revised* manuscript (**Fig. 3: line 473, Extended Data Fig. 5: line 522, Extended Data Fig. 9: line 556**).

Reviewer comment: 3.2. Plotting the vorticity (to highlight sources of the KHI) and the plasma beta (since it is refereed to in the text) in the vertical cuts would be useful in Extended Data Fig. 10, hence making it a 6-panel figure.

Our reply: We added cross-sectional cuts of the vertical vorticity (ω_z) and plasma β to **Extended Data Fig. 10 (it is now Supplementary Fig.7 in the *revised* manuscript)** in the *revised* manuscript **(line 583)**, as suggested by the reviewer.

Reviewer comment: 4. Other points to be addressed :

4.1. The origin of the shear flows is taken for granted. While it is (or may seem) obvious for convection experts, one or two sentences explaining it (e.g. following lies 102-103) could be useful for non-specialists.

Our reply: We agree, and have at the referee's suggestion added a sentence to the *revised* manuscript **(lines 106-108)** describing the cause of the shear flow: the flow components parallel to the interface of magnetic and non-magnetic regions are very weakly coupled, and as a result a misalignment of the flows to the normal of this interface can cause strong shear flows.

Reviewer comment: 4.2. The consequences of ubiquitous surface vortices in solar (and stellar) atmospheric heating could be supplemented by some sentences and references (e.g. around lines 206 and/or 214). Indeed numerous vortices most likely provide a source of small-scale but widespread flux braiding, and therefore of many overlooked small-scales in the Sun's atmosphere, that will provide electric current sheets all along the field lines anchored at the Sun's surface, independently of turbulence of vortex merging. Since this flux braiding model is one of the main ideas for coronal heating, and since it is always looking for observed sources of braiding motions, it is arguable that it should be referred to here.

Our reply: We thank the reviewer for the suggestion. We have revised the corresponding paragraph and added a discussion of the KHI as a potential source of magnetic flux braiding and its possible role in coronal heating, as suggested (**lines 29-30, 215-223**). We have also added the relevant citations **(lines 760-763)**.

Reviewer comment: 4.3. The link with Parker's 1979 reference is not so obvious. Firstly the way the present paper quotes it seems to present a contradiction. On one hand, the Summary states that the "KHI [...] supports the theory of disjoint magnetic flux concentrations [...] that _combine to form_ strong monolithic flux regions [...] as proposed by E. Parker". On the other hand the Article reads "KHI at the magnetic boundaries leads to a _fragmentation and splits_ the monolithic magnetic element [...] into individual strands below it, was originally proposed by Parker". Secondly, Parker's 1979 series addressed many physics questions, the main ideas being : (i) propagating Alfvén waves are responsible for the fragmentation below sunspots ; (ii) large-scale convective converging flows stabilize the sunspot structure. But to this reviewer's knowledge, such Alfvén waves are not seen in modern simulations. Also in the present paper, it is KHI that leads to fragmentation, and it occurs only on the edge of the flux concentrations, and all at once at every depth, more and more efficient with depth as very well explained in the present paper. Finally Cheung, Rempel, Title & Schüssler (2010, ApJ 720, 233) have actually shown the sunspot stability to be ensured by their deep magnetic roots, not by convective flows. And the same authors (like a few others) have obtained fragmented sunspots, without Alfvén waves, or KHI. In a nutshell, unless the authors provide compelling arguments, I would argue that the present KHI discovery hardly relates to Parker's 1979 ideas, that it does not need to, and that its consequences are actually much farther reaching, presumably mostly atmospheric / coronal heating.

Our reply: We agree with the reviewer that the impact of KHI on the atmospheric/coronal heating should be emphasized over that of the fragmentation process in the layers below tau=1, and have removed the citation of Parker's paper from the abstract (**lines 29-30**), and description of Supplementary Video S5 **(lines 642**).

That said, we do believe that the fragmentation process (particularly visible in the deeper, subsurface layers of the simulation) is still noteworthy in the context of magnetic field stratification and dynamics near - in this case small-scale - flux concentrations. We have clarified the text, in particular where the analogy of the picture given in Parker diverges from that given in this manuscript, and that in our case the KHI appears to be the driving force for fragmentation (**lines 182-185**).