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Diagnostic potential of Hε for small-scale energetic phenomena

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The hydrogen Balmer lines show enhanced emission in various energetic phenomena in the solar atmosphere. For example, the Hα line shows complex wing enhancements in the Ellerman Bomb phenomenon. Recently, Ellerman bombs have been detected in the Hβ line at high number densities in the quiet Sun and it was concluded that these mark the ubiquitous presence of small-scale magnetic reconnection. In this work, we explore the diagnostic potential of the 5th transition in the Balmer series, the Hε line, one of the shorter wavelength Balmer lines that promise detection of small-scale energetic events at higher spatial resolution than achieved before.

Hε is located just redward of the strong Ca H line core which poses a challenge for the understanding of the spectral line formation. To understand the formation of Hε, especially the transition from absorption to emission line, we investigate the line formation using 3D radiative MHD Bifrost simulations and NLTE forward modelling with RH. The locations where Hε goes into emission mark regions of steep chromospheric temperature enhancements and indicate regions where magnetic energy is released. Hε could be therefore a valuable tracer for small-scale energetic events in the solar atmosphere.

WHAT and WHY?

Reconnection events are ubiquitous in the solar atmosphere and appear as different phenomena depending on the atmospheric layer. We are especially interested in reconnection events located in the solar photosphere. These events are difficult to detect, especially in quiet Sun regions with weaker magnetic field. In the vicinity of sunspots with strong magnetic fields and flux emergence, "strong" photospheric reconnection events are called "Ellerman bombs" (EBs) and appear as intense brightenings of the extended wings of Hα and are invisible in the line core (Ellerman 1917). However, as photospheric reconnection events should also appear in regions with weaker magnetic fields, the question arises: how can we detect such small-scale weak reconnection events and which spectral line would be a good diagnostic tool ?

Rouppe van der Voort et al. (2016) discovered photospheric brightenings that resemble the main characteristic of EBs in quiet Sun locations and called these phenomena quiet Sun Ellerman-like brightenings (QSEBs). A subsequent study by Joshi et al. (2020) continued the characterizations of QSEBs with observations in the hydrogen Hβ line and found a significantly higher number of QSEBs. This raises the question if this brightenings play an important role in the energy budget of the lower solar atmosphere and reconfiguration of magnetic fields at photospheric heights.

Looking for new diagnostics to explore small-scale reconnection, we study the Hε line. This line appears as a weak line blend in the red wing of the strong Ca II H spectral line. Hε has two advantages compared to Hα and Hβ: higher spatial resolution (through shorter wavelength) and enhanced contrast (through wavelength dependence of the Planck function). We are particularly interested in Hε emission lines as they mark regions of temperature enhancement in the low chromosphere (Ayres et al. 1976), making Hε a good candidate to detect reconnection events in the deep solar atmosphere.

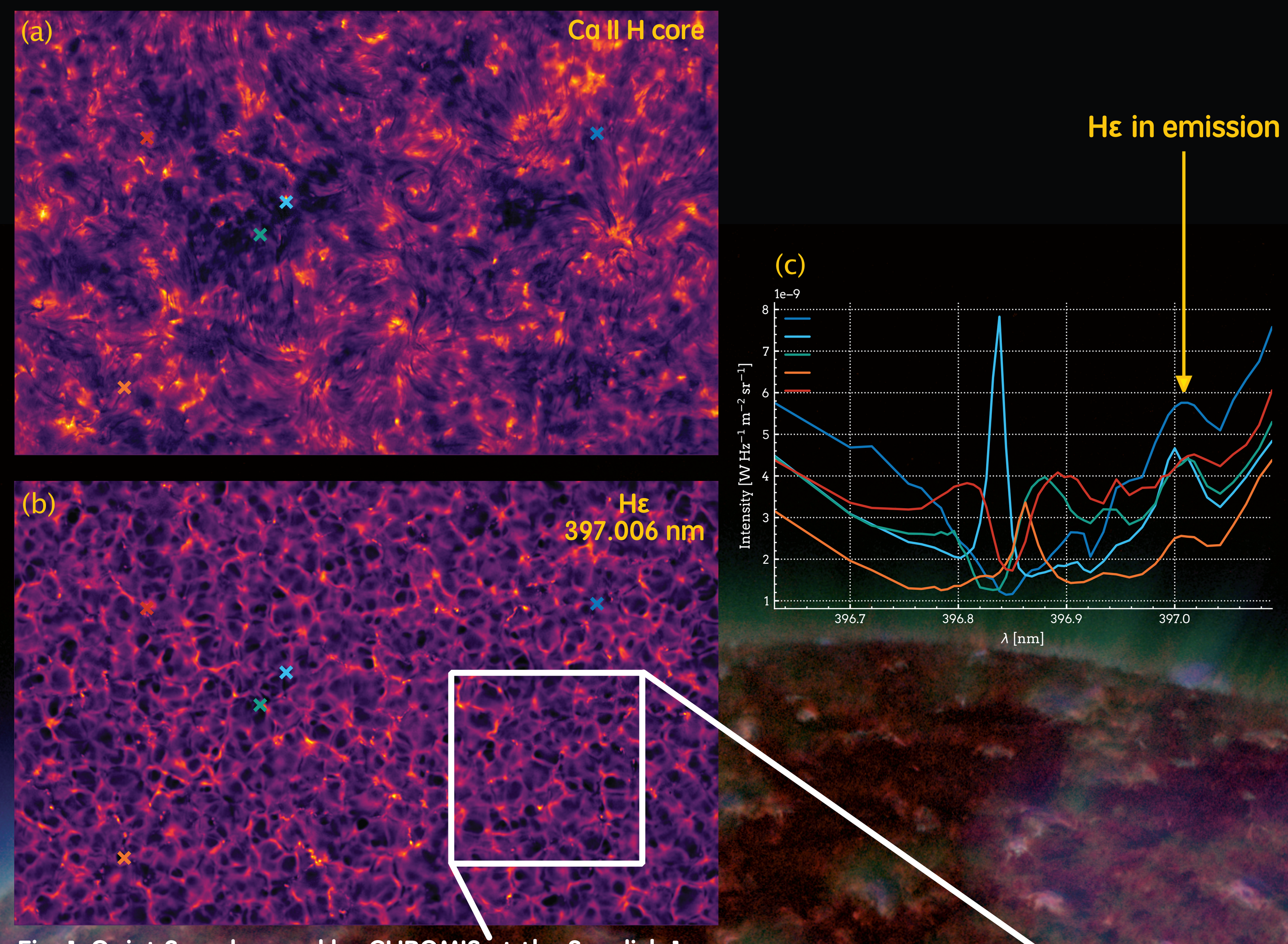

Fig. 1: Quiet Sun observed by CHROMIS at the Swedish 1-m Solar Telescope. (a) Ca Hε core. (b) Hε core. The crosses mark regions with Hε emission, whose individual spectra are shown in (c).

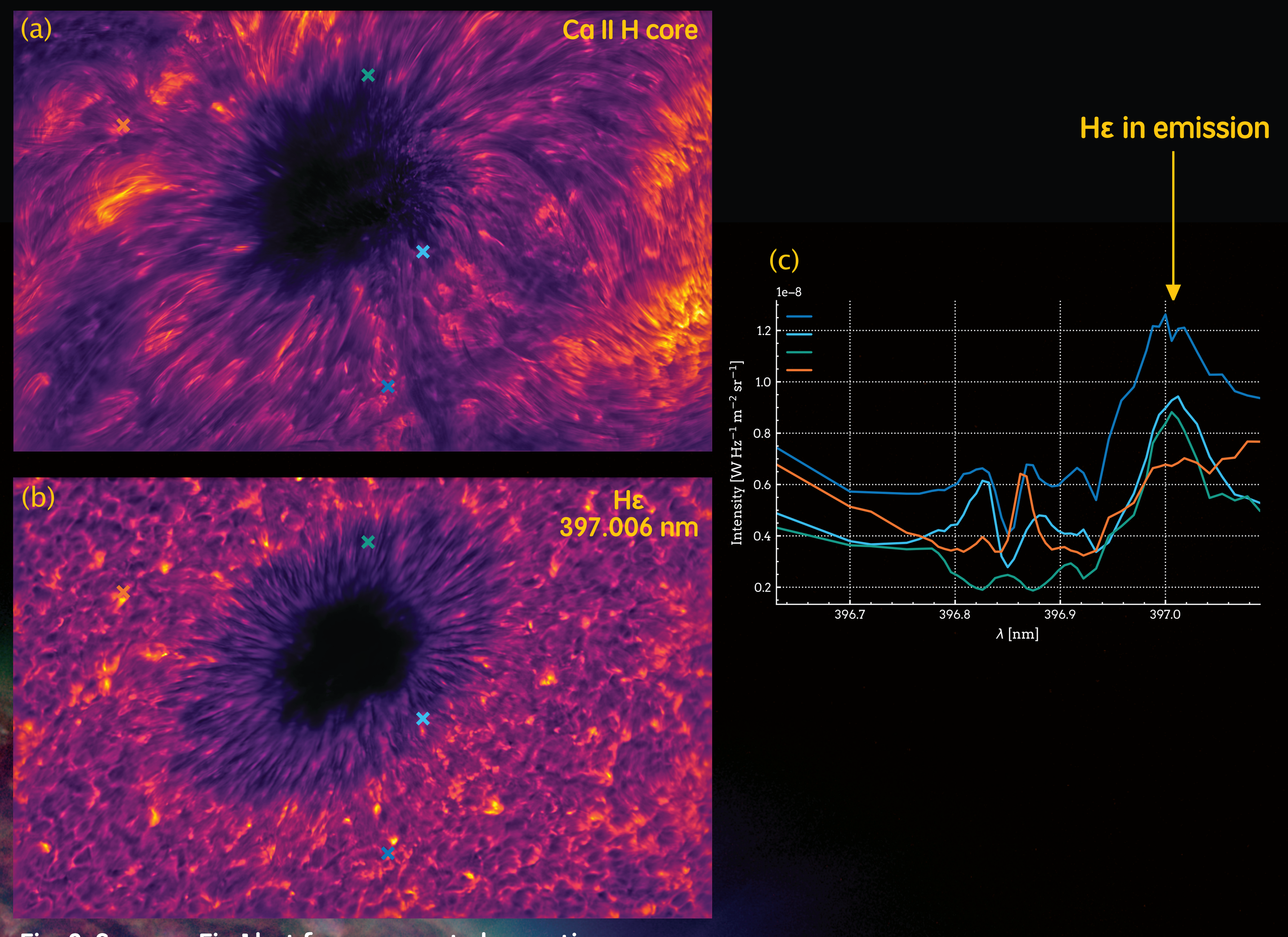

Fig. 2: Same as Fig.1 but for a sunspot observation.

HOW?

To study the formation of Hε, we use a Bifrost simulation of solar enhanced network (EN) from Carlsson et al. (2016) and non-LTE spectral synthesis with partial redistribution. We synthesise both the Ca II H and the Hε lines using the RH 1.5D code (Pereira & Uitenbroek 2015).

Throughout the chromosphere the ionization state of hydrogen is strongly affected by non-equilibrium ionization (NEI) effects and coupled to the Balmer continuum radiation field. We include the effect of non-equilibrium ionization in the RH code by keeping the ionized population of hydrogen constant, as the simulation treats hydrogen in NEI. The modeled Balmer continuum accounts for line blanketing in the Balmer continuum wavelength range.

We compute the contribution functions for relative absorption or emission at each atmospheric height following Magain (1986). Because Hε lies on the wing of the much stronger Ca II H line, we calculate the formation of Hε relative to the Ca II H wing.

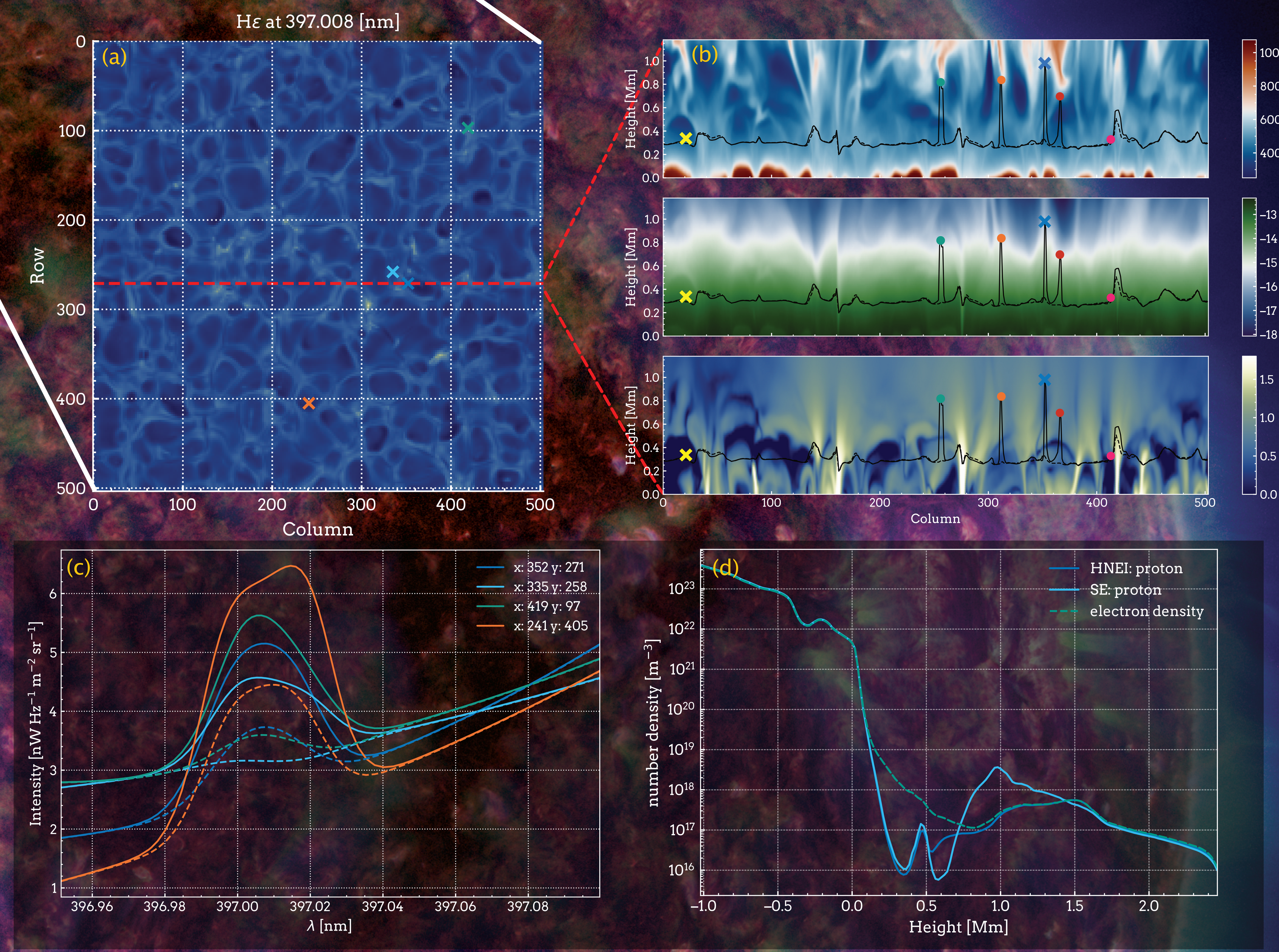

Fig. 3: Synthetic Hε spectra from the Bifrost EN simulation. The horizontal extent is 24x24 Mm^2, with 504x504 grid points (96 km pix^{-1}). (a) emergent radiation at rest wavelength of Hε. (b) vertical cuts for temperature, gas density, and magnetic field at the dashed red line. The black lines show the τ=1 height in SE (solid) and H-NEI (dashed). Markers on black lines indicate regions of emission in Hε for SE (filled circles and crosses) and H-NEI (only crosses). (c) individual Hε spectra from selected points, marked with crosses in (a), where Hε is in emission, for SE (solid lines) and H-NEI (dashed lines). (d) proton and electron densities in the atmosphere for the position (x, y)=(352, 271), marked with a blue cross in (a).

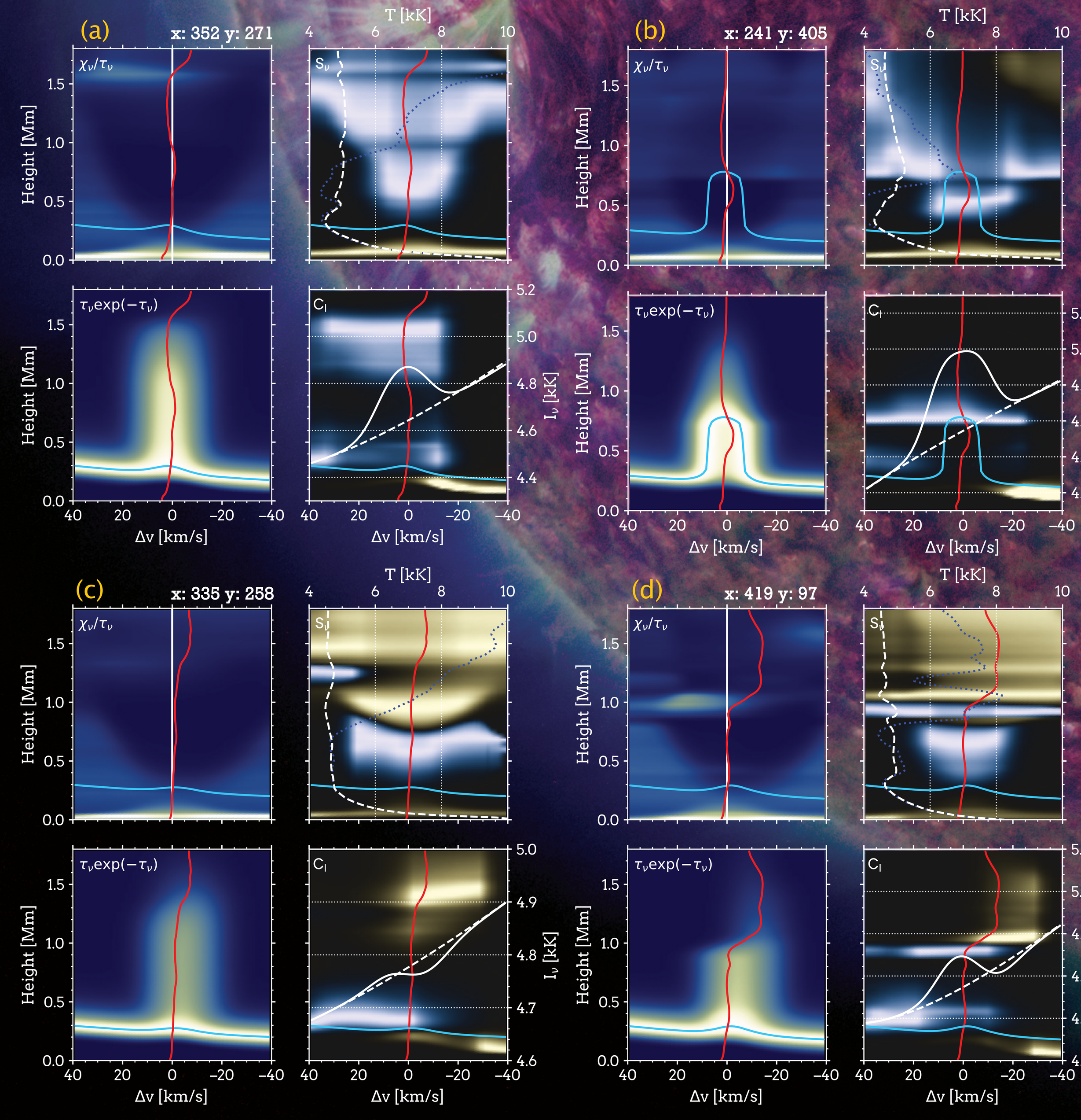

Fig. 4: Four-panel formation diagrams for Hε, for the four points marked with crosses in Fig. 3a. For each diagram, the top and bottom left panels show the factors that compose the contribution function for intensity, shown at the bottom right. Also, the panels on the right have colour maps centered around zero, with blue showing negative values (contribution to relative emission), and yellow showing positive values (contribution to relative absorption). Red lines show upward velocity and cyan lines show the τ=1 height. In the top right panels, the dotted blue line shows the gas temperature and the dashed white line the total source function at the rest wavelength. In the bottom right panels, the spectra are shown in white for Ca II H with Hε (solid line) and Ca II H only (dashed line).

RESULTS

We found multiple examples of Hε in emission in the EN simulation. In particular, it occurs in locations that have a steep temperature rise through the chromosphere, marking regions where the chromosphere is heated. Regions with Hε emission are generally found inside granules, in intergranular lanes where multiple granules meet and at bright features which seem to connect granules. Non-equilibrium hydrogen ionization affects the formation of Hε. Compared to SE, we find fewer regions with emission lines and the emission is itself weaker.

We conclude that Hε could be a valuable tracer for small-scale heating events with photospheric origin heating the lower chromosphere.

Acknowledgements

This research is supported by the Research Council of Norway through its Centres of Excellence scheme, project number 262622 and from European Research Council Synergy grant WHOLE SUN 810218. The Swedish 1-m Solar Telescope is operated on the island of La Palma by the Institute for Solar Physics of Stockholm University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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