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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, Ellerman bombs show complex wing enhancements in the Hα line. Recently, Ellerman bombs have been detected in the Hβ line at high number densities in the quiet Sun and it was suggested that these mark the ubiquitous presence of small-scale magnetic reconnection. In this work, we explore the diagnostic potential of the Hε line, one of the shorter wavelength Balmer lines that shows promise to detect small-scale energetic events at even higher spatial resolution.

Hε is located just redward of the strong Ca H line core, which poses a challenge to understand its formation. We investigate how Hε forms in 3D radiative MHD simulations of the solar atmosphere, using the Bifrost code together with the RH code for NLTE spectral synthesis. Of particular interest are regions where Hε goes from absorption to emission, which suggest heating in the lower atmosphere, most likely from the release of magnetic energy. Hε could therefore be 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 flields 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.

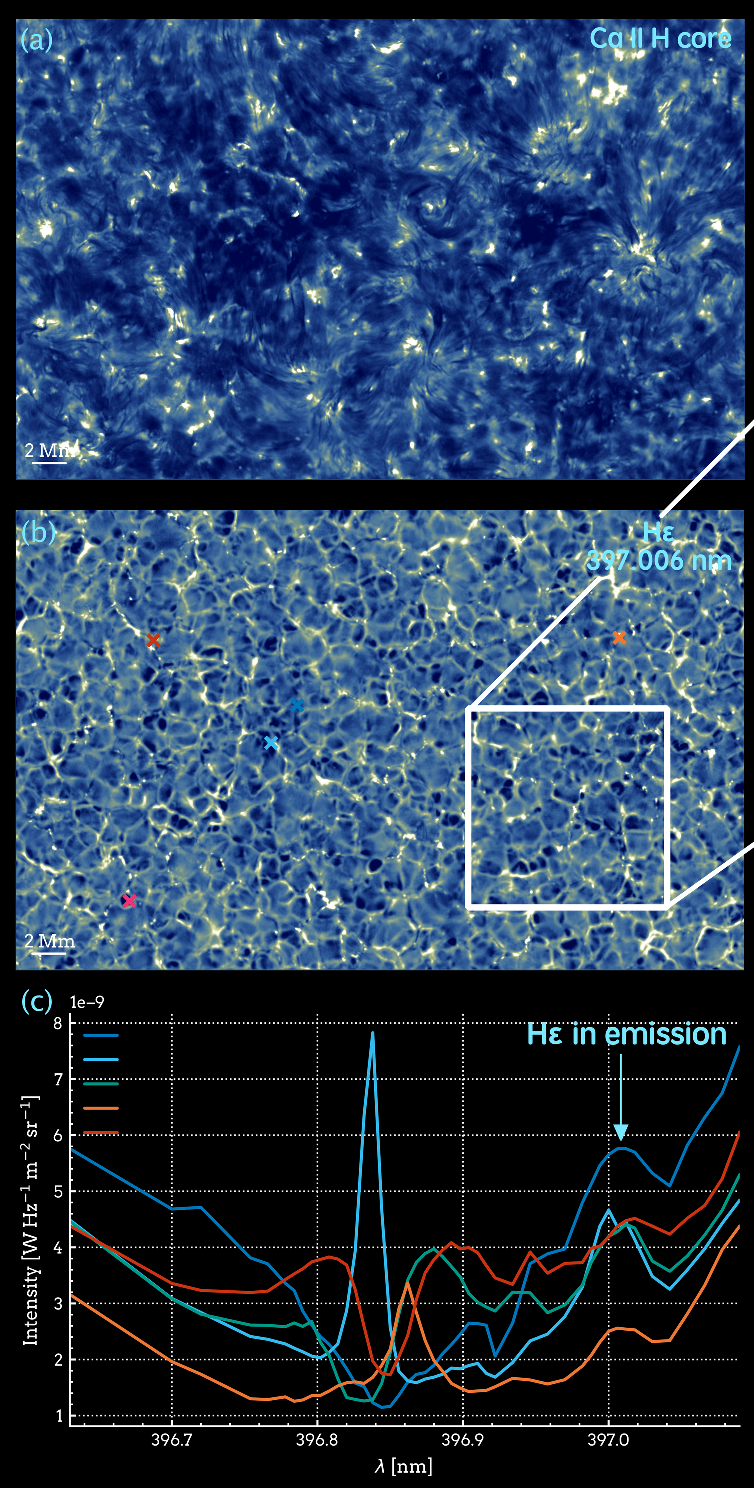

Fig. 1: Quiet Sun observed by CHROMIS at the Swedish 1-m Solar Telescope. (a) Ca H core. (b) Hε core. The crosses mark regions with Hε emission, whose individual spectra are shown in (c).

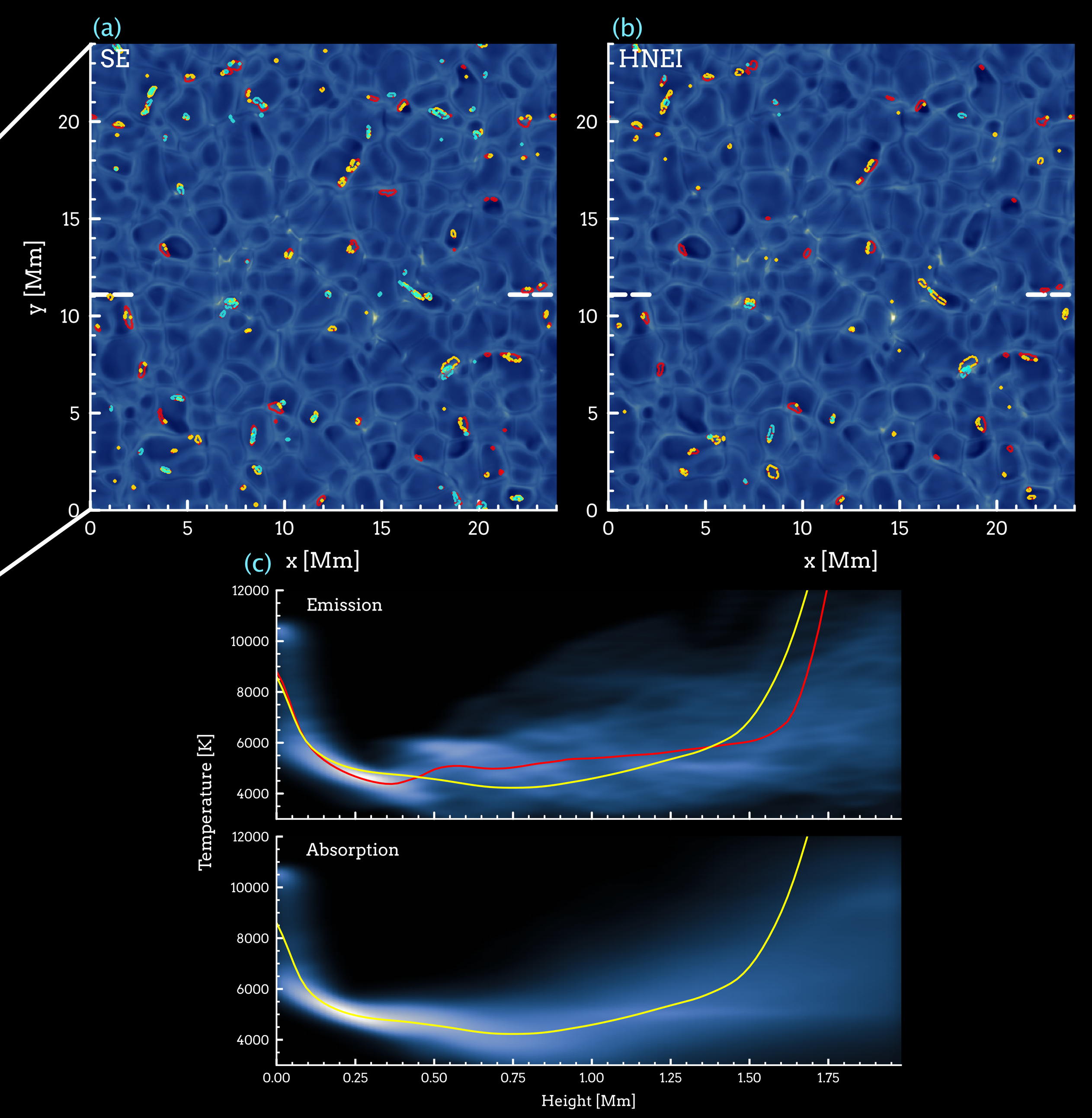

Fig. 2: Hε line core images for the SE (a) and HNEI (b) case synthesised from the EN simulation. Red, yellow, and cyan contours mark regions of Hε emission for different τ=1 column masses. Kernel density estimation of temperature profiles related to Hε emission and absorption line locations show in (c). Yellow and red solid line outline the average temperature profile for absorption and emission line locations.

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 and RH 1.5D code (Uitenbroek 2001, 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.

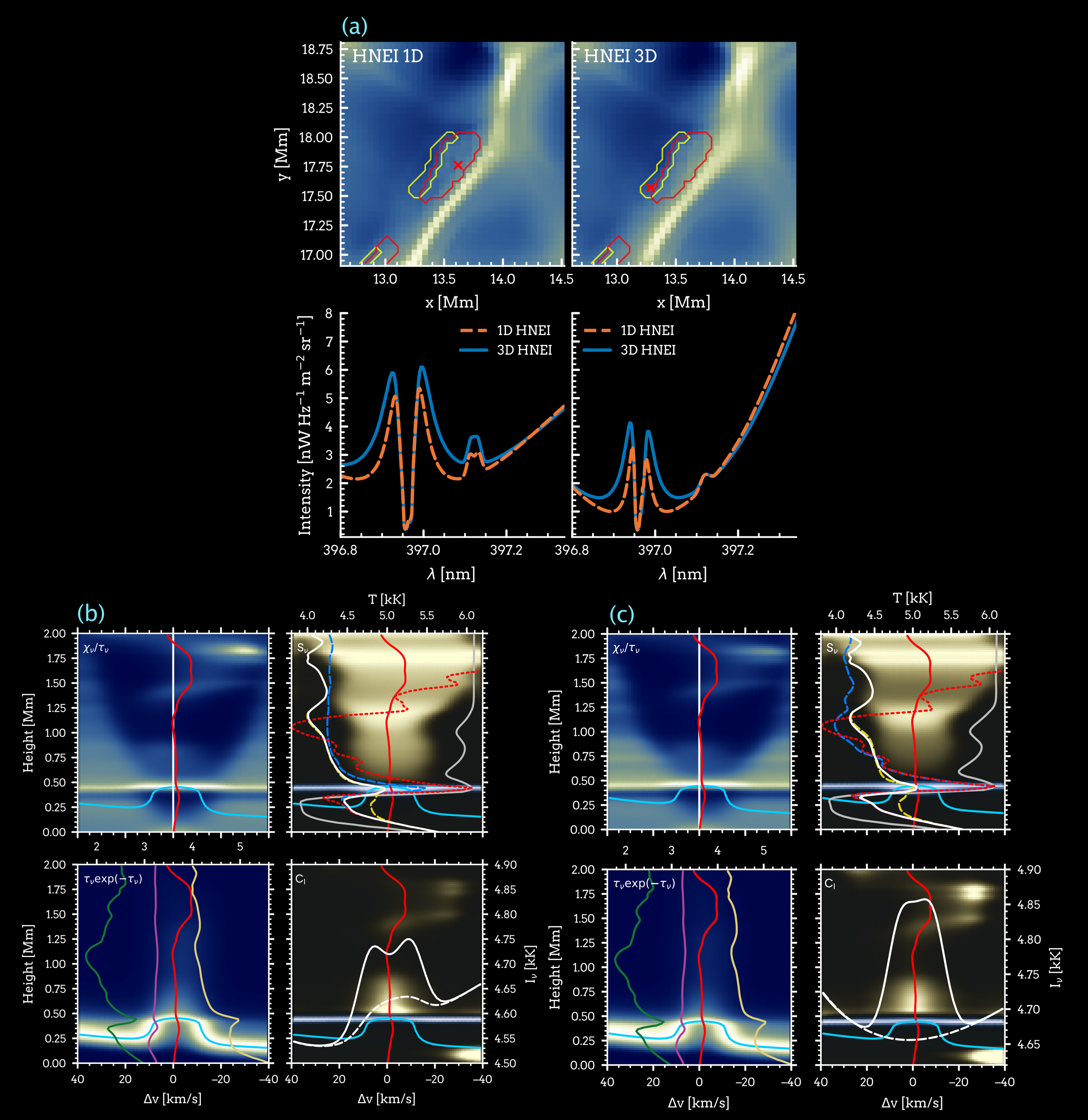

Fig. 3: Four-panel formation diagrams for Hε, for the region marked with a cross in left panel of Fig. 3a. For each diagram, the top and bottom left panels show the factors that compose the relative contribution function for intensity, shown at the bottom right. The panels on the right have colour maps 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 red line shows the gas temperature, the solid white line the total source function, blue dashed line the background source function, orange dashed line the Hε source function at rest wavelength, and grey solid line shows the relative line extinction to total extinction. Solid green, violet, and gold line show the relative thermal, scattering, and interlocking contribution to the Hε source function. 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).

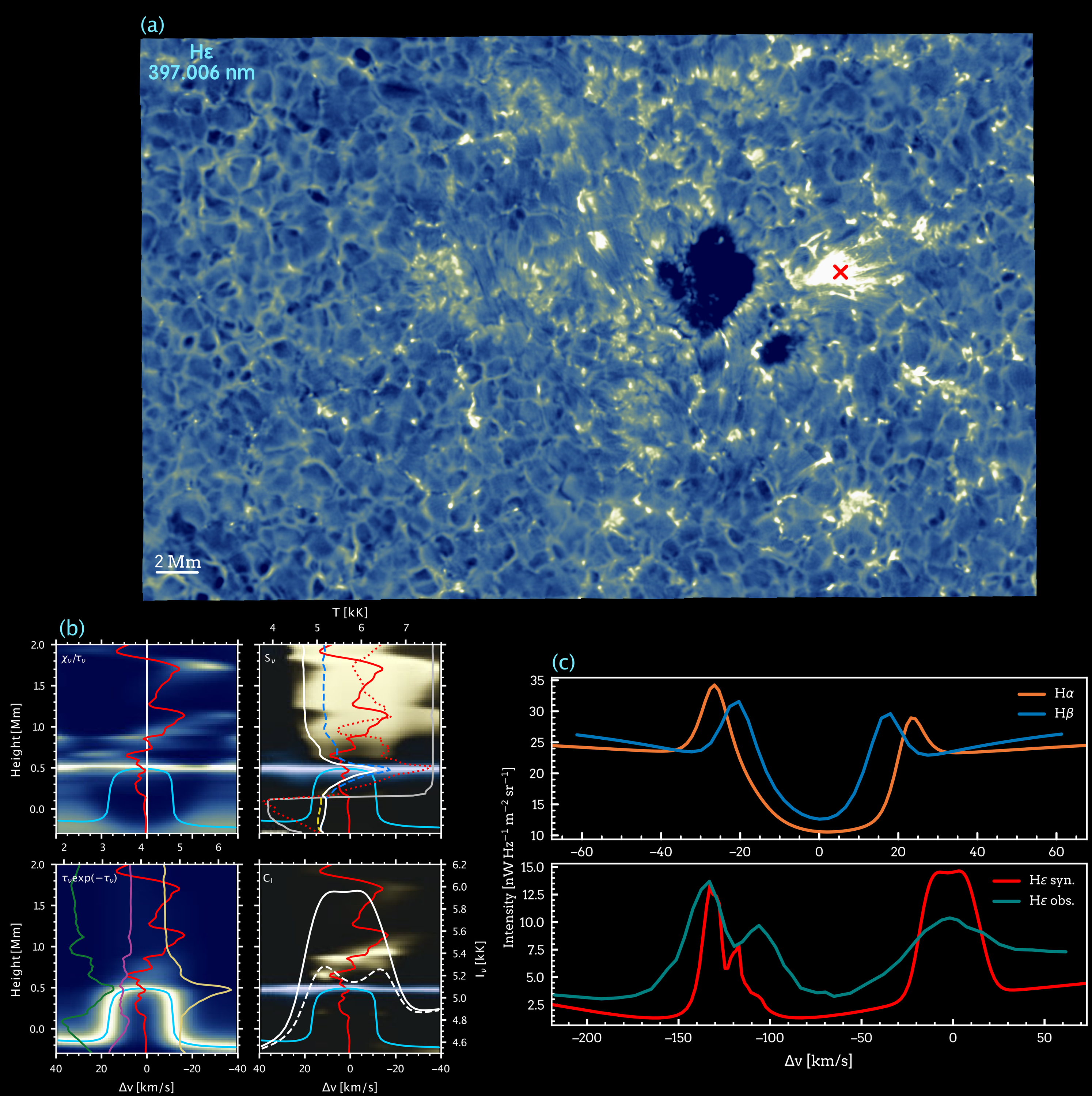

Fig. 4: Pore observation in the Hε line core taken with the CHROMIS instrument at the Swedish 1-m Solar Telescope. Red cross marks the region of the profile shown in (c). Hε four-panel formation diagramm for the moustach EB profiles shown in (c) from a column taken from the spicule simulation by Martínez-Sykora et al. 2017. Panel (c) shows synthesised Hα, Hβ, and Hε against an observed Hε profile.

RESULTS

We found multiple examples of Hε in emission in the EN simulation and quiet Sun observation taken with CHROMIS. In particular, it occurs at locations where we see enhanced temperatures at mid photospheric height without a traditional temperature minimum. The temperature sensitivity of Hε comes from the interlocking term in the source function with dominant collisional leakage from the first energy level to the upper energy level of Hε. Further, non-equilibrium hydrogen ionization affects the formation of Hε, by weakening the temperature sensitivity of the Hε opacity and coupling it to the ionized hydrogen population.

We conclude that Hε is a valuable tracer for small-scale heating events with photospheric origin heating the solar lower atmoshpere.

Topics

- Small-scale flux emergence
- Weak granular field interaction
- Quiet Sun Ellerman-like brightenings
- Footpoint heating of coronal loops

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