The Bright Rim Prominences according to *Lightweaver* ✨ 2.5D Radiative Transfer

The cause and effect of radiation trapping

Dr. Jack M. Jenkins

jack.jenkins@conict.be

Incoming ESA Research Fellow, ESAC, Madrid

Osborne, C., Qiu, Y., Keppens, R., Li, C.

AIM

Explore to what degree the radiative interaction found in the infinite 1.5D prominence models can influence their multidimensional counterparts.

APPROACH

- Build and test a proof of concept 2.5D radiative transfer experiment that, in a single atmosphere, includes the chromosphere, corona, and prominence

- Derive synthetic metrics in preparation for a statistical comparison against observations

METHODOLOGY

Construct a 'toy model' that mimics the Magnetohydrostatic (MHS) heritage models through a combination of tanh() profiles. This ensures we have control over the resolution of the model grid, so as to focus it where we need it e.g., the prominence-coronal-transition-region (PCTR)

- Adopt a modified (radiative equilibrium for a vertical field) VAL-3C model (Carlsson + 2023) as the chromosphere - transition region - corona. Regrid to focus set resolution at positions of sharp gradients
- Embed an elevated condensation within the coronal portion at 8000 K, and 0.2 dyn cm^{-2}, with extents 2(H) and 5(V) Mm, set to the shape of a squircle to avoid numerical oscillations at the corners. Ensure it connects smoothly to coronal temperatures
- Modify quadrature prescription to reduce spotlighting of backscattered radiation on underlying chromosphere. Consider both nonSymmetric and equal-weighting prescriptions.

TOOLKIT

- *Lightweaver* ✨, non-LTE radiative transfer, including overlapping transitions, assuming Partial Frequency Redistribution (PRD), accounting for photoionisation whilst fixing the initial pressure:

SCAN ME

$$\sum_{j\neq i} n_j P_{ji} - n_i \sum_{j\neq i} P_{ij} = 0. \qquad P_{ij} = R_{ij} + C_{ij},$$

$$\mu \frac{\partial I(\nu, \mathbf{d})}{\partial z} = \eta(\nu, \mathbf{d}) - \chi(\nu, \mathbf{d}) I(\nu, \mathbf{d}),$$

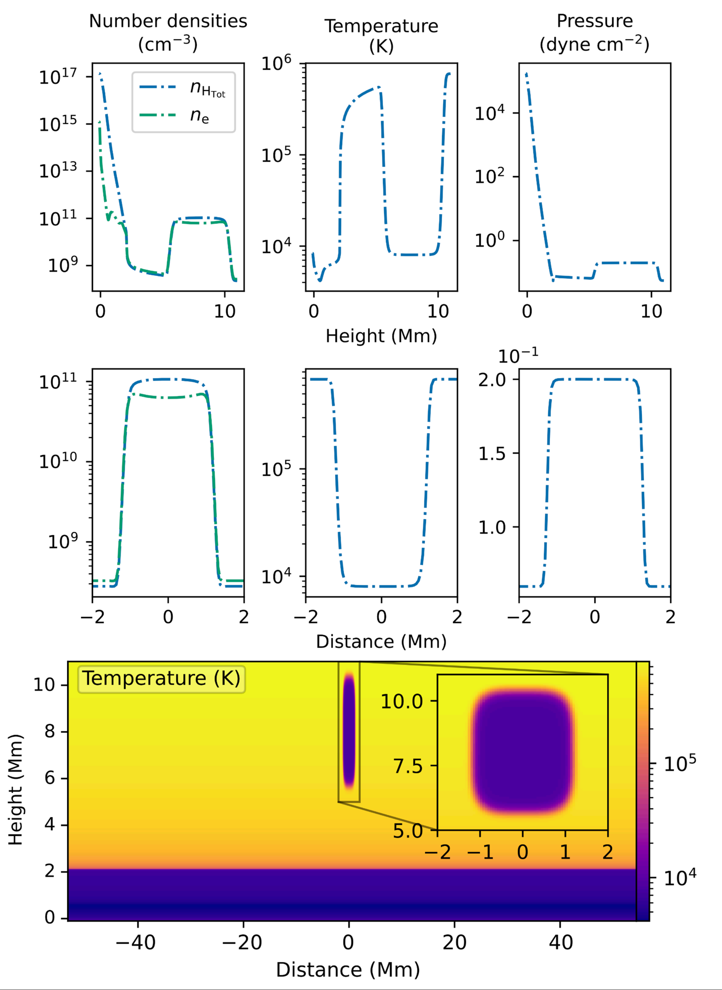
KU LEUVEN

erc European Research Council

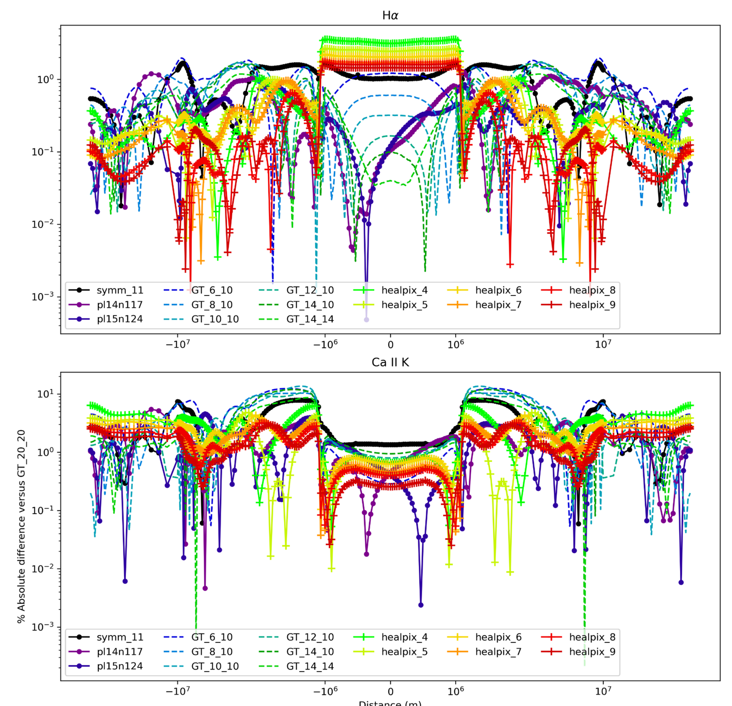
VLAAMS SUPERCOMPUTER CENTRUM — Vlaanderen is supercomputing

MODEL & MACHINERY

We began by constructing an artificial atmosphere with a prominence embedded out of hydrostatic equilibrium, as below.

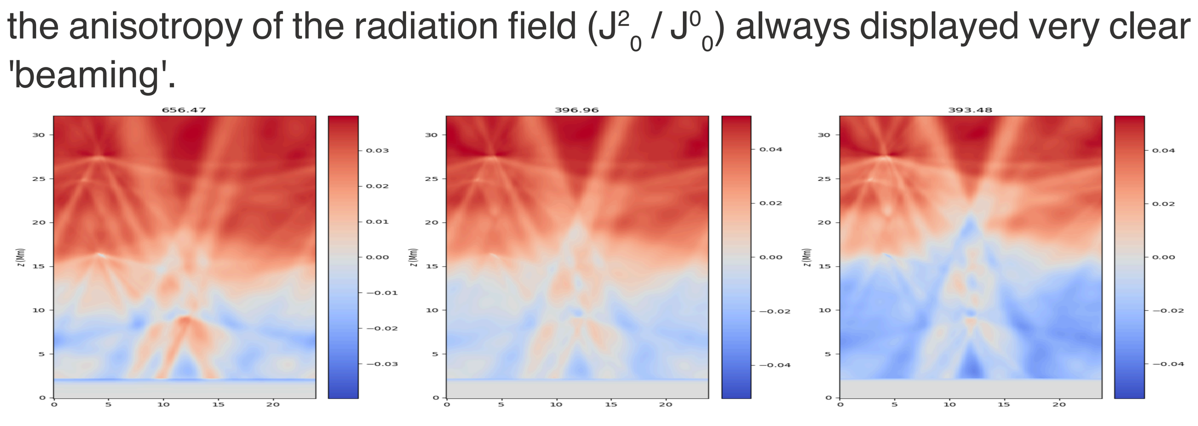


We solved for statistical equilibrium using the short characteristics approach under many quadrature approximations.



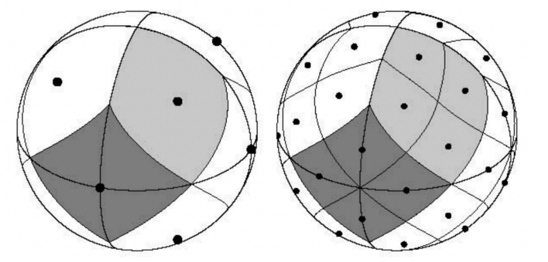
We found the results to be incredibly sensitive to the chosen quadrature, shown here as abs(relative difference of I_θ) against the Gauss-Trapezoidal (GT) 20 20 (400 ray) solution, the often-considered ground truth.

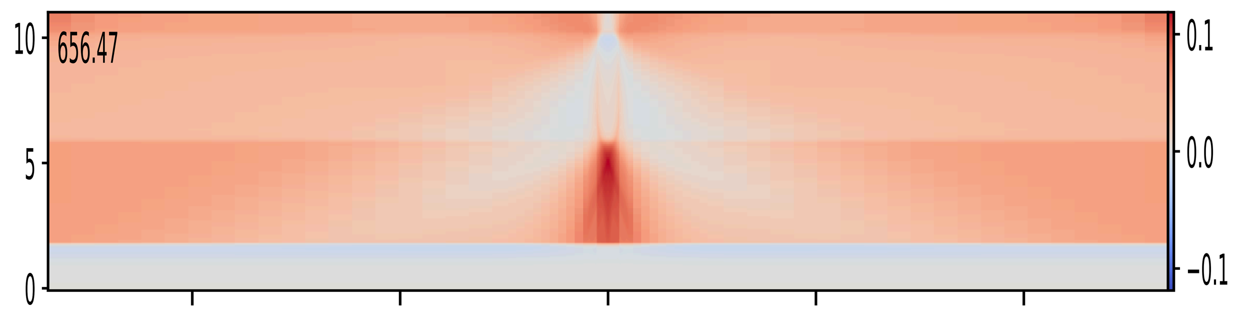
Whether we adopted symmetric quadratures (the famous A sets), the equivalent optimised by Stepan+(2020), the nonSymmetric examples of Jaume Bestard+(2021), or even very dense GT sets (~1000 rays), the anisotropy of the radiation field (J^2_0 / J^0_0) always displayed very clear 'beaming'.



* particular example from an MHD prominence with fine structure, stretched for emphasis

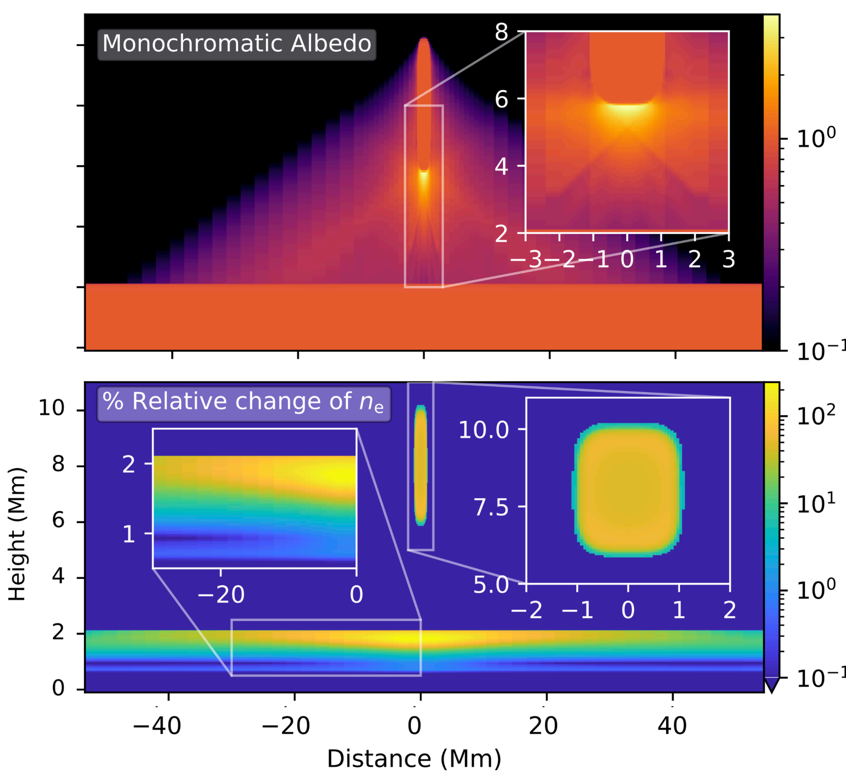
We instead opted for a HEALPix quadrature (Górski+2005), a slightly more computationally expensive 'equal weighting' approach but one that all but eliminates the chromospheric beaming.



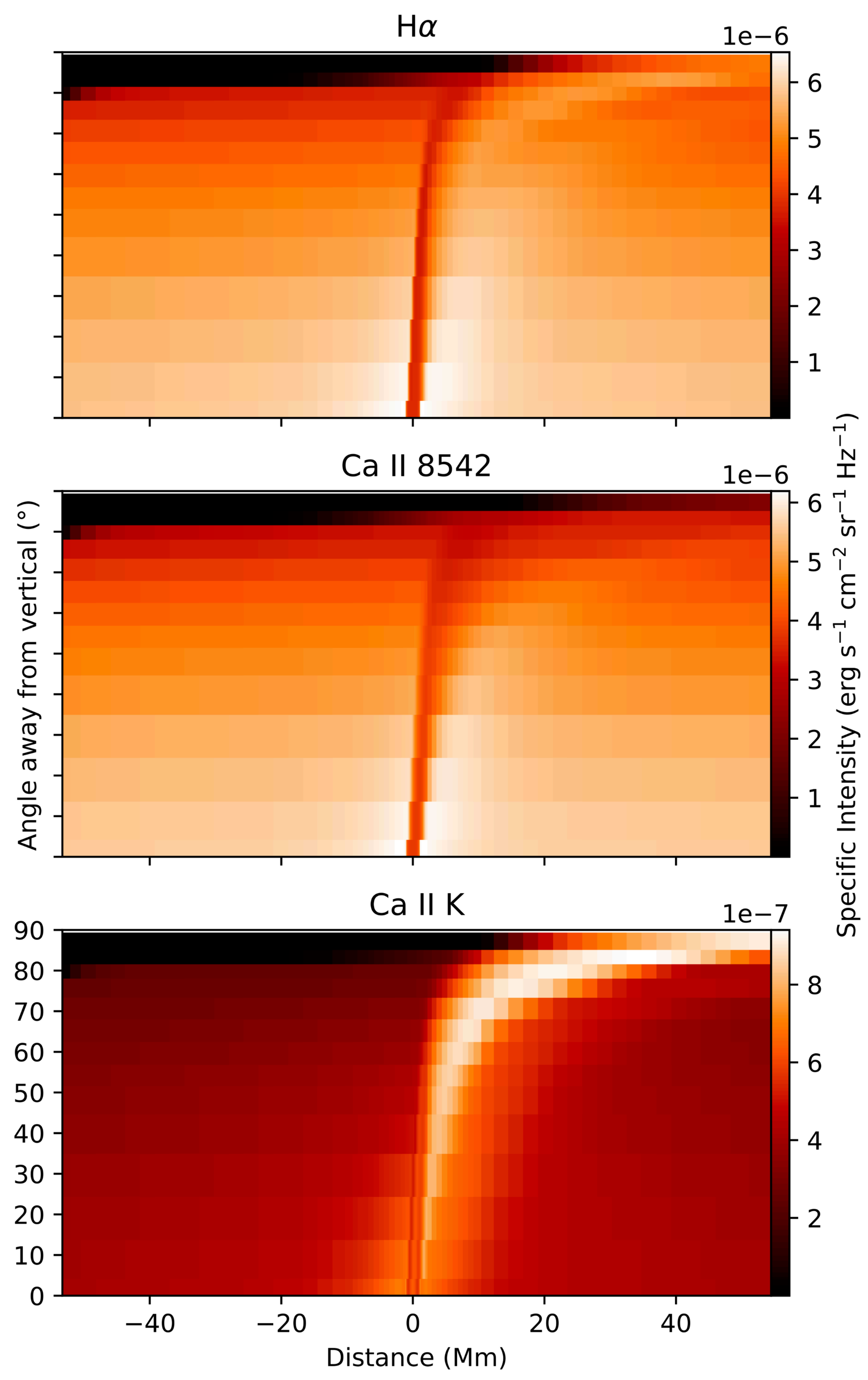


CHROMOSPHERE---- PROMINENCE INTERACTION

Our converged solution suggests that prominences can be highly reflective, as demonstrated by the large angle-integrated albedo (for the Lyman continuum head) of the toy model (see also Paletou+(1993)). Such reflected ionising radiation not only initially modifies the electron number density within the prominence, but also the populations within the underlying chromosphere.



For those transition lines considered within the model convergence, this interaction leads to a brightening visible either side of the absorption typically recovered for the 'filament' projection, that is, viewing from top-down. By inclining the viewing angle to mimic a disk transit towards the limb, this brightening becomes, in all cases, skewed in the direction of the observer, in turn revealing a secondary brightening.



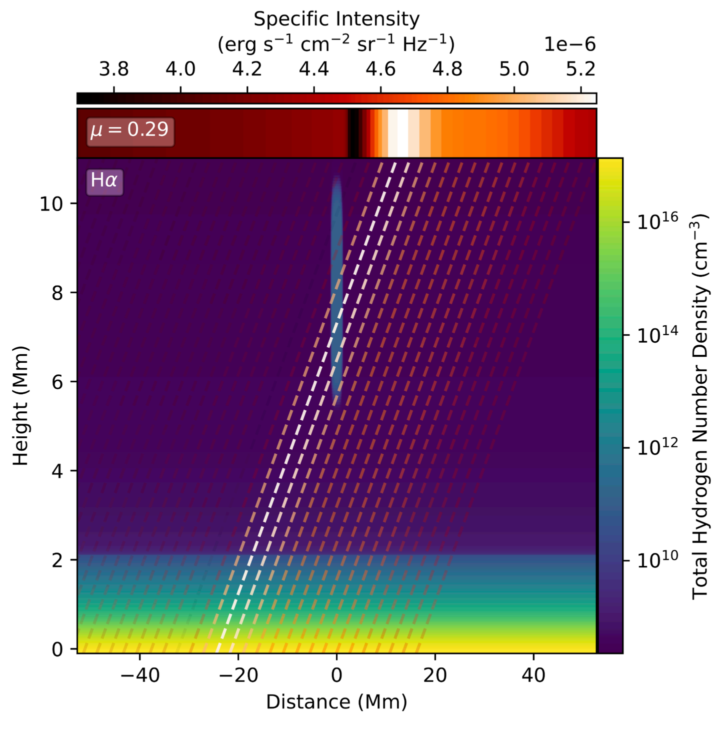
As the view angle is increased...

Hα: the initially symmetric brightening becomes more diffuse whereas the secondary brightening grows in extent and its contrast against the background chromosphere increases until the entire prominence appears bright at the limb against the background of space.

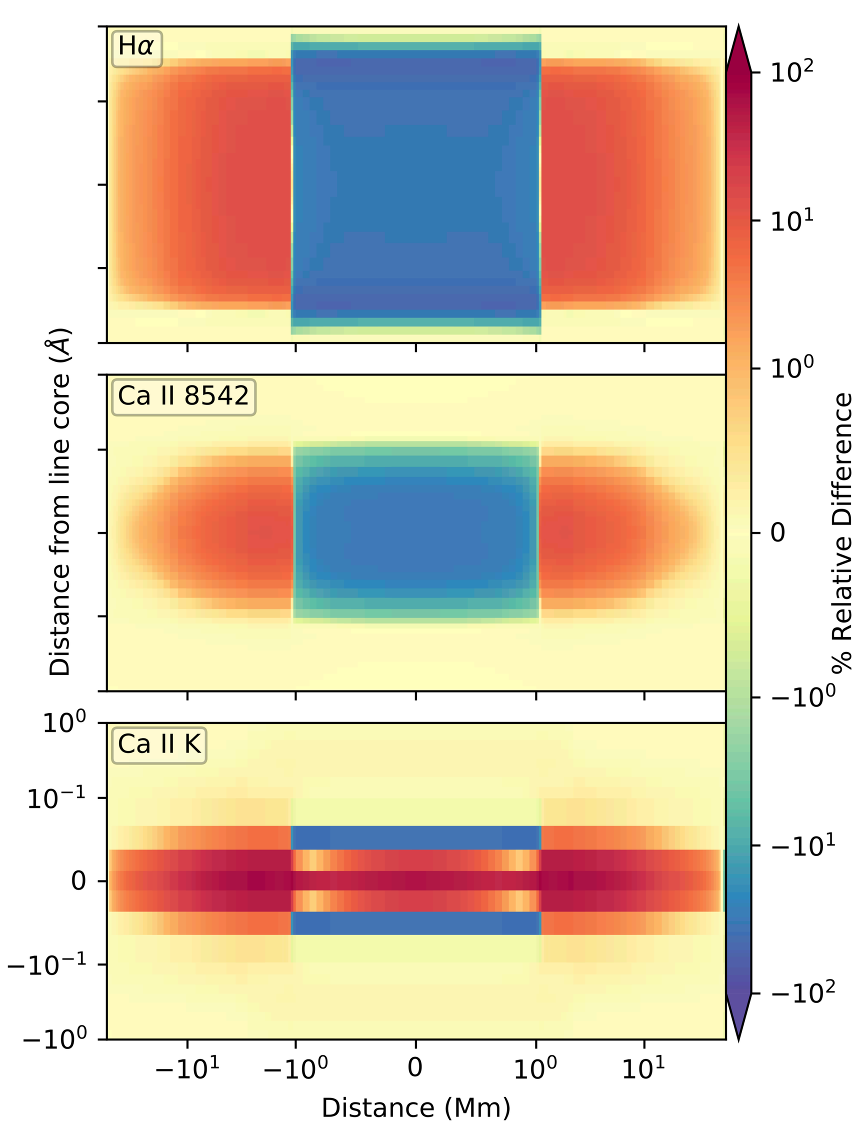
Ca II 8542: the initially symmetric brightening becomes more diffuse, a secondary brightening does not appear.

Ca II K: the initially symmetric brightening becomes more diffuse and the secondary brightening quickly renders the filament in positive contrast against the solar disk.

Focusing on Hα, an inclined viewing angle details from exactly where the two distinct brightenings are sourced. The more diffuse originates from the underlying chromosphere whose n_e population is enhanced by the backscattered radiation, whereas the brighter and more localised emission is sourced from the underside of the prominence itself (cf. Heinzel 1995).



Whether it's the enhancements in the n_e population, or the subsequent increase in intensity, the influence of the backscattered radiation has a limited spatial range; the albedo indicates this to be dependent on the extent of the prominence itself. Under the initial condition of a static model, the same symmetry is found spectrally, with the largest influence of the backscattered radiation recorded for the line core (where the prominence plasma is most optically-thick), and tapers off with increasing Δλ. Relative difference here is versus chromospheric illumination.

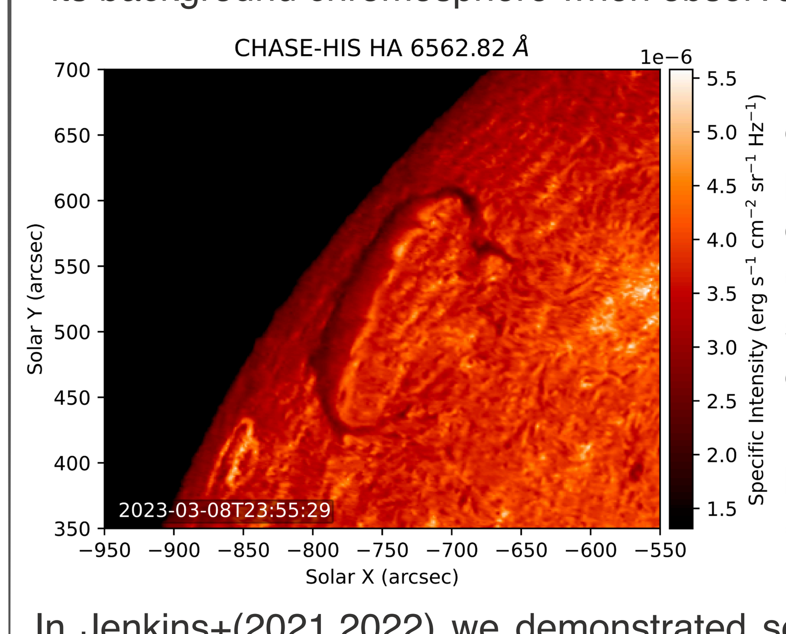


As for the line core emergent intensity, changing the viewing angle leads to a skewing of the spectral response in space, that further evolves as the filament approaches the simulated solar limb (not explicitly shown here).

Such behaviour will undoubtedly increase the parameter space available to spectral inversions, further complicating such efforts. That said, constraining such additional features may aid in selecting a model out of the sea of common degeneracies.

Regardless, we must first constrain our own results to be sure this theoretical proof-of-concept is physically accurate.

Prominence 'Bright-Rims' have been observed since observations of the Sun in Hα became common place. As also well-captured by the most modern instrumentation available, such as *CHASE/HIS*, Bright-Rims describe the thin line of positive contrast often visible at the projected interface between a filament and its background chromosphere when observed close to the solar limb.



Despite being so well observed, a comprehensive description of this phenomena is still outstanding despite a range of proposed theories. Our simplified model already suggests that this brightening may be caused, at least in part, by the radiation trapping beneath a solar prominence. What we require now are less-artificial models.

In Jenkins+(2021,2022) we demonstrated self-consistent MHD models of solar prominences. In Jenkins+(2023), and again here, we have demonstrated multi-dimensional radiative transfer models from which we may glean observationally comparable metrics. The next step is to merge these efforts and directly compare against observations.

In Summary

This proof of concept represents the first 2(.5)D radiative transfer model of solar prominences to encompass an underlying chromosphere and surrounding corona. Our results offer a potential explanation for the long-observed 'Bright-Rim' phenomenon, but it is clear that improvements are needed (just look at Ca II K...). Whether we complete a statistical comparison against observations, or focus on the base thermodynamics, there is plenty to keep us busy.