Setting observational constraints to the chromospheric heating problem

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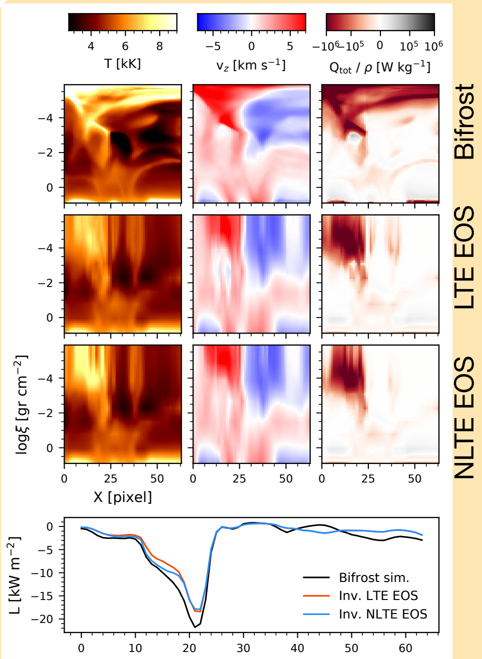
The solar atmosphere is hotter than predicted by assuming radiative equilibrium. This is most obviously evidenced by the high temperature of the solar corona, but the bulk of the energy deposition happens already down in the much cooler chromosphere. While in recent years we have gain detailed understanding of many important processes that must be at work in the chromosphere, also from numerical simulations, their exact contribution to the total energy budget remains unclear.

Chromospheric heating or cooling can be estimated by calculating the radiative losses whenever a model atmosphere is available. Most comparisons between simulations and observations have used canonical values of radiative losses that have been derived from 1D models of spato-temporal averages of solar spectra (e.g., FAL / VAL models). Such approach cannot capture the high complexity and fine structures that is observed in high resolution observations. Recent studies have evidenced that spatially resolved radiative cooling can be up to five times higher in active regions than those canonical values that are usually assumed. Our current estimates are losses of approximately 4 kW m^2 in the quiet Sun and 20 kW m^2 in active regions.

We present spatially resolved radiative cooling rates computed from the inversion of high spatial resolution chromospheric datasets observed with the Swedish 1-m Solar Telescope in Ca II K, 8542 and Fe I 6301/6302. We study the distribution of radiative cooling across the FOV in different targets in active regions and in quiet-Sun. Our results will help modellers to set better constraints on theoretical predictions and models.

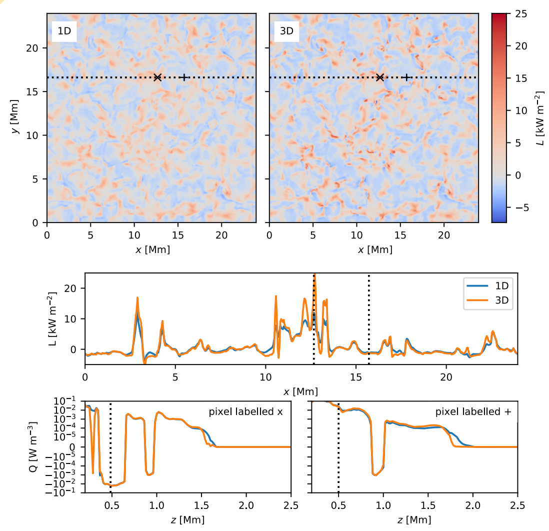


Numerical tests: reconstruction of shocks

Our tests show that our Ca II / Fe I dataset inversions can reconstruct a shock atmosphere. The main source of error in the reconstruction originates from having a limited depth resolution and the imposition of hydrostatic equilibrium to derive a gas pressure scale.

The derived integrated losses (bottom panel) have been estimated using an LTE equation of state (red) and including the effect of H ionization in statistical equilibrium, while imposing charge conservation. We hace included the contribution of the main chromospheric bound-bound and bound-free transitions in H, Ca II and Mg II.

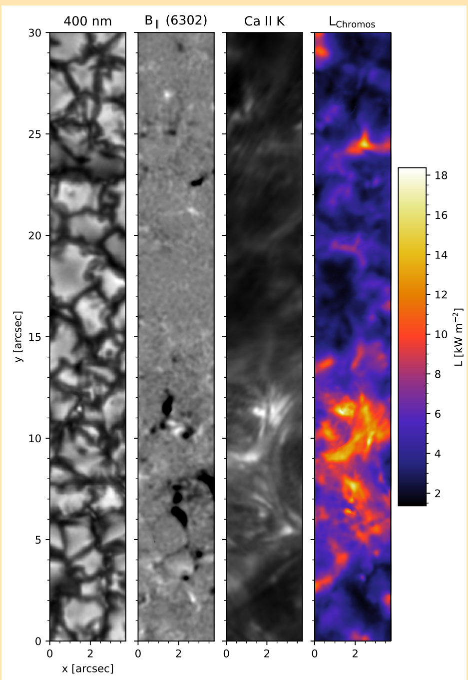
Numerical tests: 3D radiative transfer effects



Our results suggest that 3D radiative transfer effects are not a dominant source of error when estimating integrated radiative losses.

Our tests are performed using a 3D rMHD *Bifrost* simulation (Carlsson et al. 2016) and the Multi3D code (Leenaarts & Carlsson 2009). We have repeated the calculations using a 3D solver and a 1D plane-parallel solver

Radiative losses in quiet Sun

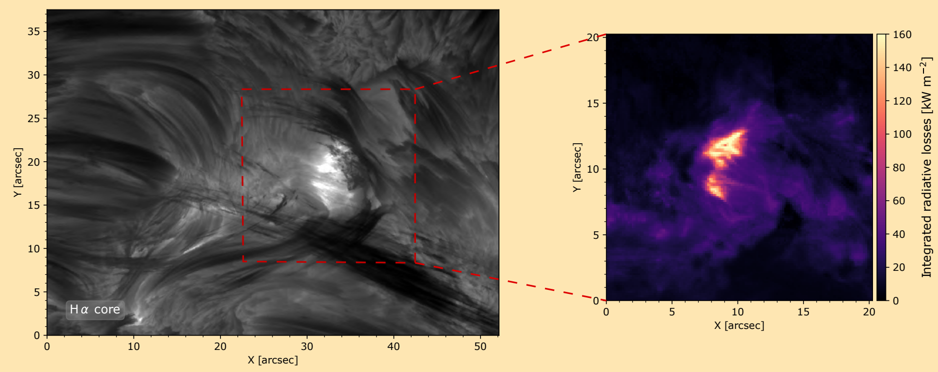


Our results show that the presence of magnetic field concentrations (see bottom area) and waves lead to a finely detailed map of radiative losses.

While the canonical value of 4 kW m^2 seems to be representative of a large fraction of the FOV, we find regions with significantly larger heating, peaking at 18 kW m^2.

de la Cruz Rodriguez & Leenaarts (in prep.)

Radiative losses in an active region



In this AR undergoing magnetic flux cancelation, we found chromospheric radiative losses up to a factor 5x - x8 larger than the canonical values for such targets, showing the importance of magnetic fields in the heating of the solar chromosphere.

Diaz Baso et al. (2021), figure courtesy of C. Diaz Baso.

Summary

- We have estimated spatially resolved radiative losses from observational data of the solar chromosphere.
- Our results show finely structured and highly corrugated maps of radiative losses
- We find radiative losses up to a factor x8 higher than the canonical values.
- Peak values in QS and AR are located around the strongest magnetic field concentrations.

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Established by the European Commission

I gratefully acknowledge funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement 759548)