Simulating nanoflares in the solar atmosphere

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Introduction

Solar flares play a key role in the dynamics of the solar atmosphere. They occur with a wide range of energies, from the largest X-class flares representing some of the most violent releases of energy in the solar system, to the tiny nanoflares whose faintness imposes a considerable observational challenge for current telescopes.

Nanoflares are believed to occur in great numbers, and their collective heating has been proposed as a possible explanation for the high temperature of the corona. Although existing 1D numerical models have provided great insight into the behaviour of individual flares, realistic 3D simulations are needed to examine how flares collectively influence the atmosphere.

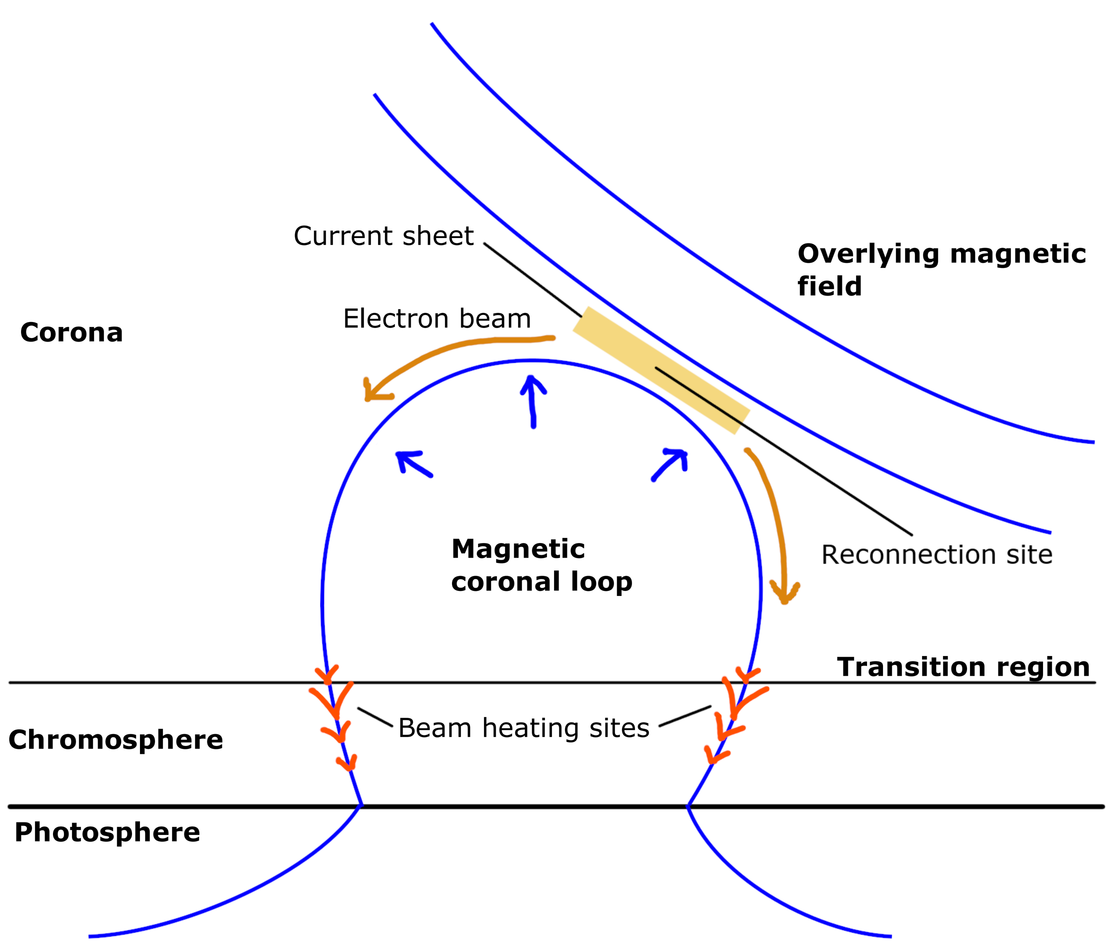

Figure 1: Basic model of solar flares. The merging of separate magnetic domains in the corona (reconnection) leads to the formation of a current sheet where electrons are being accelerated to high energies. The accelerated electrons travel along the coronal magnetic field until they encounter the denser transition region and chromosphere, where they deposit their energy as heat.

Objectives

1. **Implement a flare model in a realistic 3D atmosphere.**
2. **Use it to study the collective effect of small flares.**

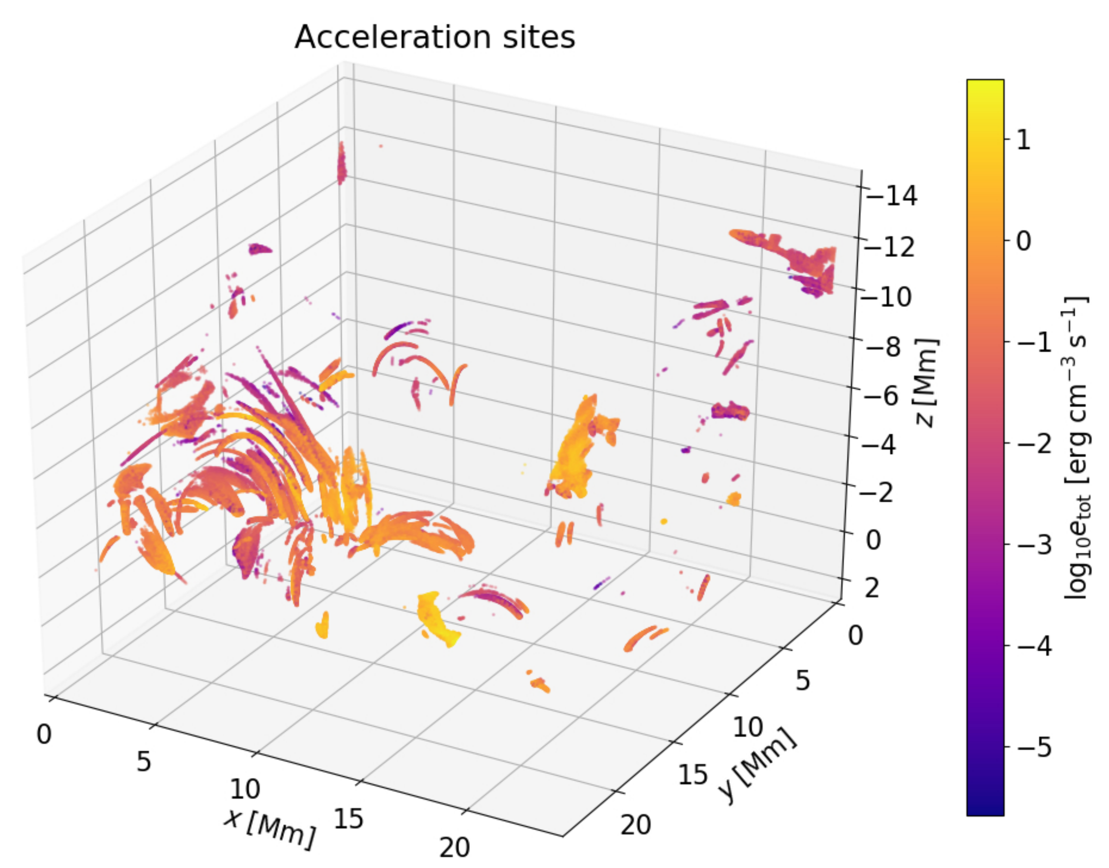

Figure 2: Points where reconnection is detected in a simulation. The colours indicate the total beam energy.

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Method

A numerical model for the generation and evolution of accelerated electron beams was developed and integrated into the 3D radiative magnetohydrodynamics code Bifrost (Gudiksen et al. 2011).

The model tackles four primary tasks:

1. Detecting electron acceleration sites
A value representing the amount of reconnection is computed at every point from gradients in the magnetic field.
2. Determining the electron energies
The energy distribution is computed as a power law with parameter values based on the local conditions.
3. Tracing the trajectories of the electron beams
An adaptive Runge-Kutta scheme is used to trace magnetic field lines passing through the acceleration sites.
4. Computing the amount of heat they deposit
An expression derived from simplifications of the Fokker-Planck equation is used.

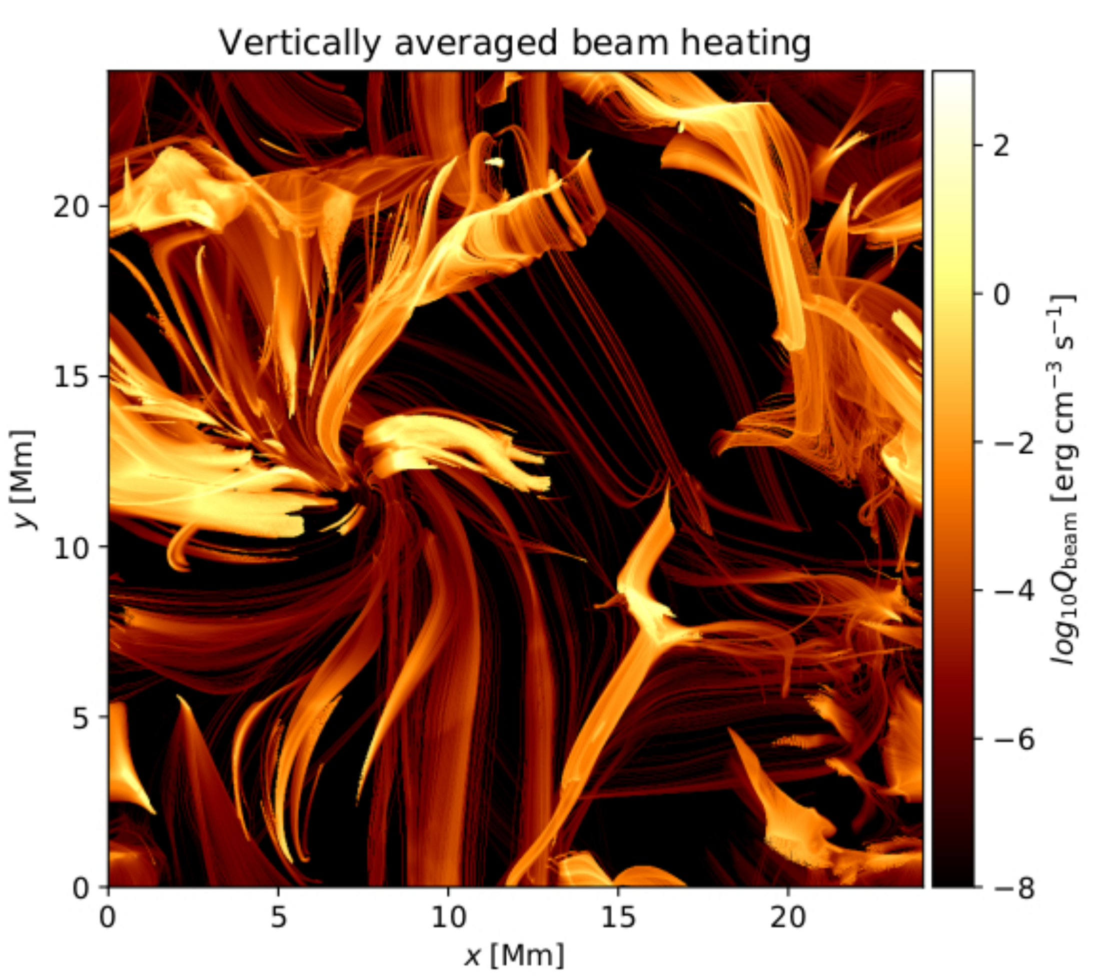

Figure 3: Rate of plasma heating that is due to the electron beams in the simulation box, averaged over all depths.

Results

A realistic simulation of the solar atmosphere was run with the electron beam physics included.

We find a reduction in the amount of detected reconnection sites (Figure 2) compared to the case without beams. The cause of this is still under investigation, but related to the removal of heat from the sites.

Regions of strong beam heating are produced in the lower transition region, at locations where magnetic coronal loops are anchored in the lower atmosphere (Figure 3). The heat input shifts the transition region downwards locally by approximately 10 km (Figure 4). As density increases with depth, this leads to higher temperatures for plasma at a given density (Figure 5). Synthetic spectra reveal resulting small brightenings in the Mg II h & k spectral lines (Figure 6). The lines are also blue-shifted by several km/s due to an increase in pressure that accelerates the plasma upwards.

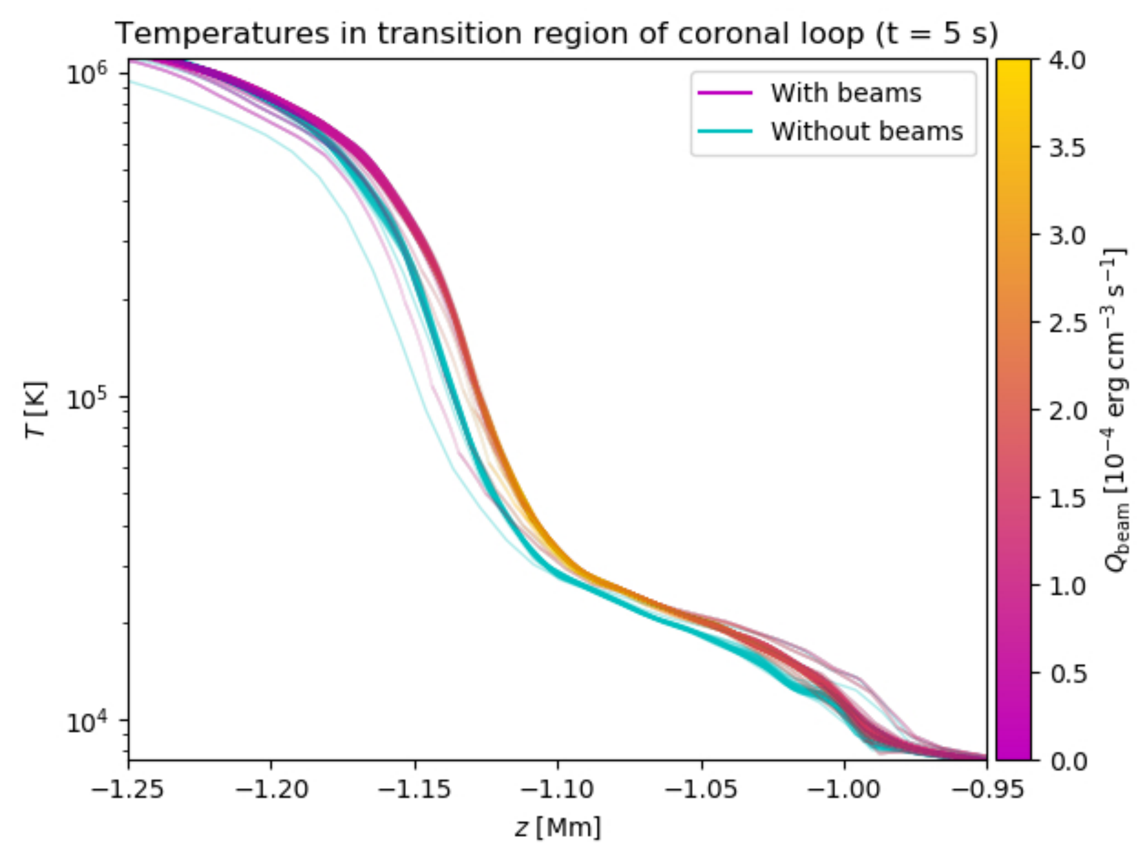

Figure 4: Temperature as a function of depth along coronal loop field lines near an intense beam heating region. The field lines from the simulation with beams are colour coded with the amount of heating that was produced by the beam traversing each field line.

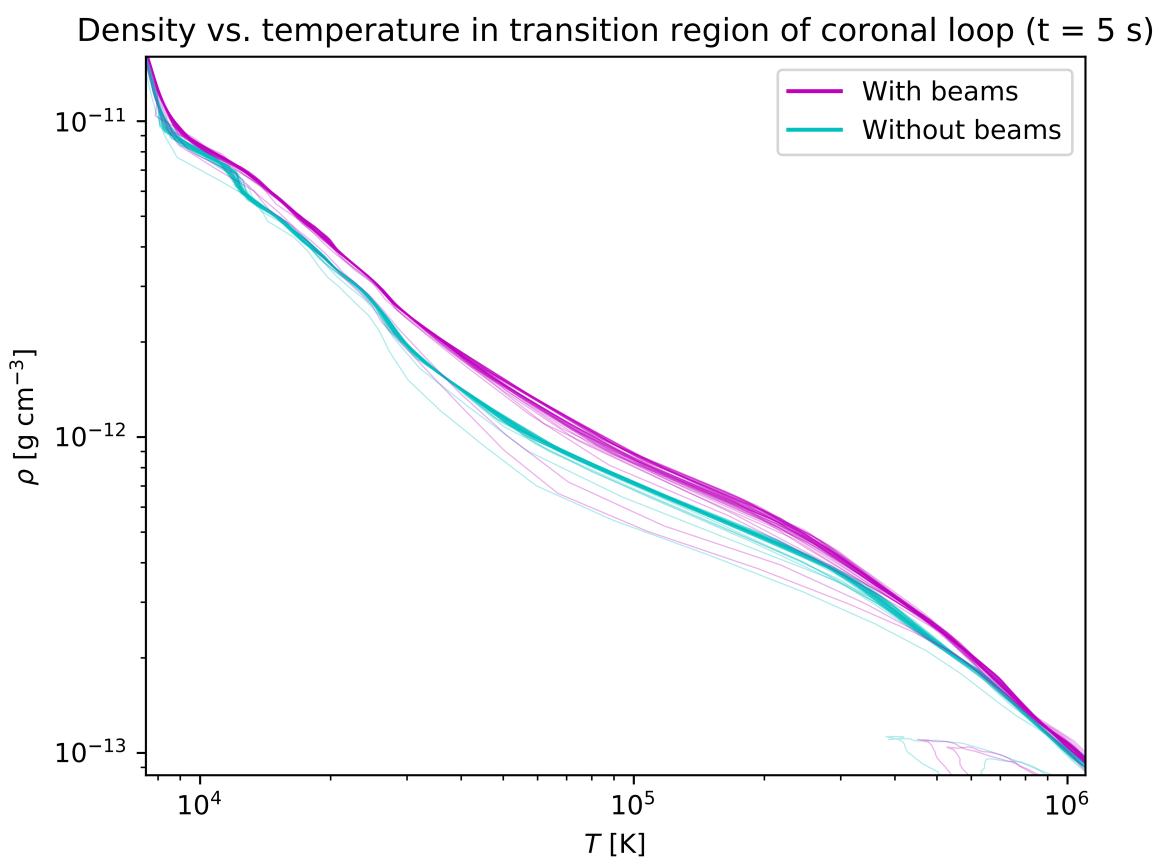

Figure 5: Density as a function of temperature along the same field lines as in Figure 4.

Conclusions

Electron beams are a mechanism of transporting energy released during reconnection from the corona to the transition region and chromosphere. In our simulations, even though they have relatively little magnetic activity, this is enough to alter the detailed structure of the corona and enhance the emission in some of the main observable spectral lines of the chromosphere. Further reading: Bakke et al. (2018)

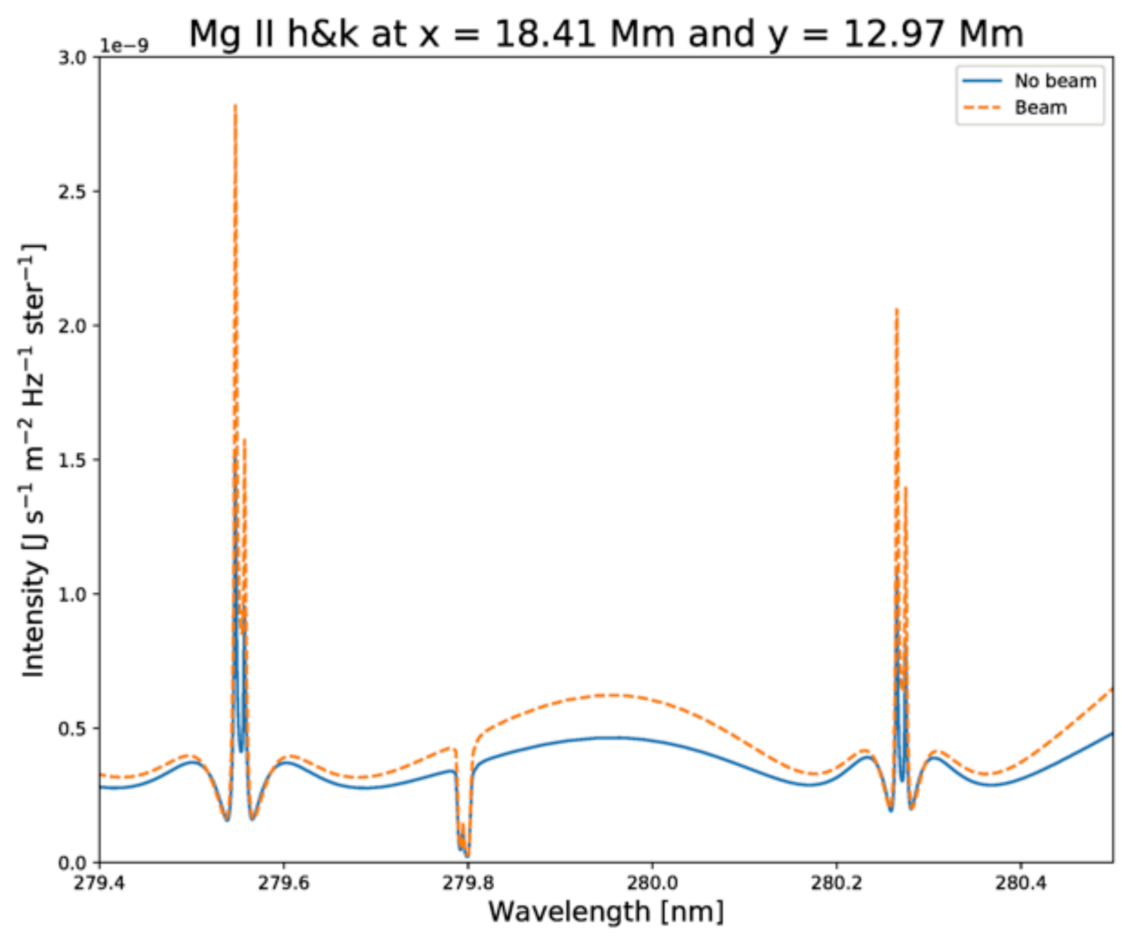

Figure 6: Synthetic spectrum from a beam heating region, containing the chromospheric Mg II h & k emission lines. The corresponding spectrum from a control simulation without beams is included for reference. Note that this figure is from a different atmosphere than the other figures.

References

Bakke, H., Frogner, L., & Gudiksen, B. V. 2018, A&A, 620, L5
Gudiksen, B. V., Carlsson, M., Hansteen, V. H., et al. 2011, A&A, 531, A154