3D Radiative MHD Modeling of Particle Beam Heating of the Solar Atmosphere

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Background and Motivations

Solar flares release vast energy across the EM spectrum; However white-light flares (WLFs) are not entirely understood.

Standard Model (Thick-Target Framework)

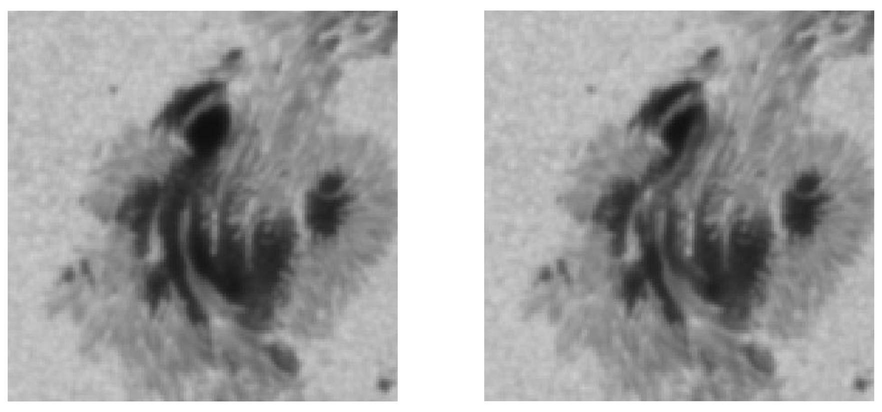
- Accelerated electrons travel from the corona to chromosphere.
- Energy deposited via collisions results in heating + hydrodynamic response.

Problem

- Models predict heating mainly in upper chromosphere and weak photospheric response.
- Photospheric observations of WLFs (SDO HMI) reveal strong continuum brightening, Fe I 6173 Å line-core emission, and Helioseismic signals (sunquakes).

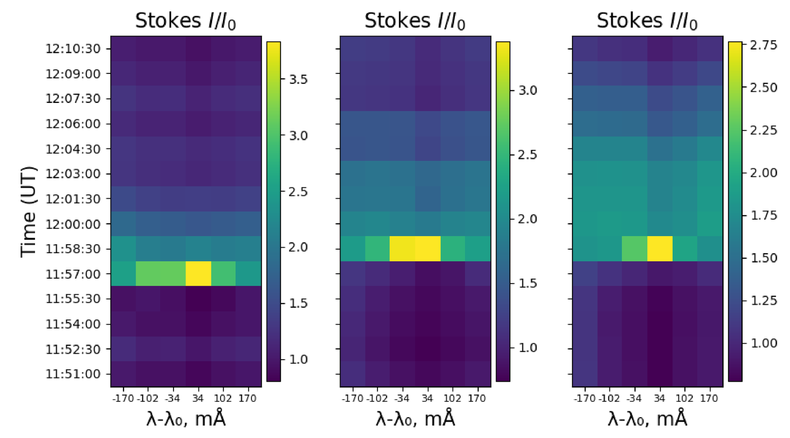
Key Question: Can electron beams modeled in realistic 3D atmospheres produce the deep heating required to explain observed white-light emission and other photospheric effects?

September 6, 2017 X9.3 White-Light Flare



11:55:30 UT   11:58:30 UT

HMI Stokes I vs Time (3 Locations)



Methods

3D Radiative MHD Simulations

- StellarBox code: 3D radiative magnetohydrodynamics (MHD) code that self-consistently models solar convection, magnetic fields, and radiative transfer, producing realistic, self-consistently evolving solar atmospheres from the subsurface to the corona.
- Domain:
  - Subsurface to corona (z = -10 to +15 Mm)
- Beam parameters:
  - Flux Ef = 10^{12} erg s^{-1} cm^{-2}
  - Spectral index δ = 3
  - Low-energy cutoff Ec = 10–25 keV

Beam Implementation

- Prescribed thick-target heating
- Vertical injection from top of domain
- Time-dependent, spatially localized beam

Spectral Diagnostics

- Code: RH 1.5D
- Synthetic observational data:
  - Fe I 6173 Å line (HMI observable)
  - Full Stokes profiles

Comparison Baseline

- 1D models: RADYN (F-CHROMA grid)

StellarBox: Atmospheric Response

What we see in 3D:

- Strong heating primarily in the lower corona and upper chromosphere
- Formation of multiple shock fronts, chromospheric condensations, and bubble-like structures.

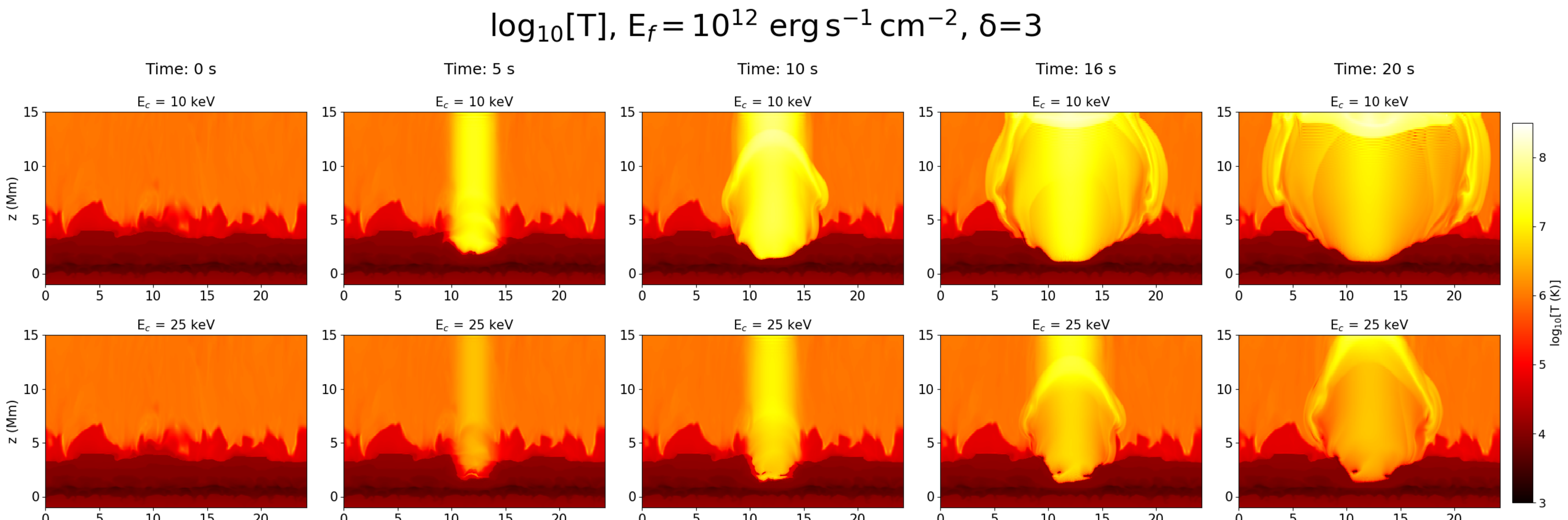
Dynamics:

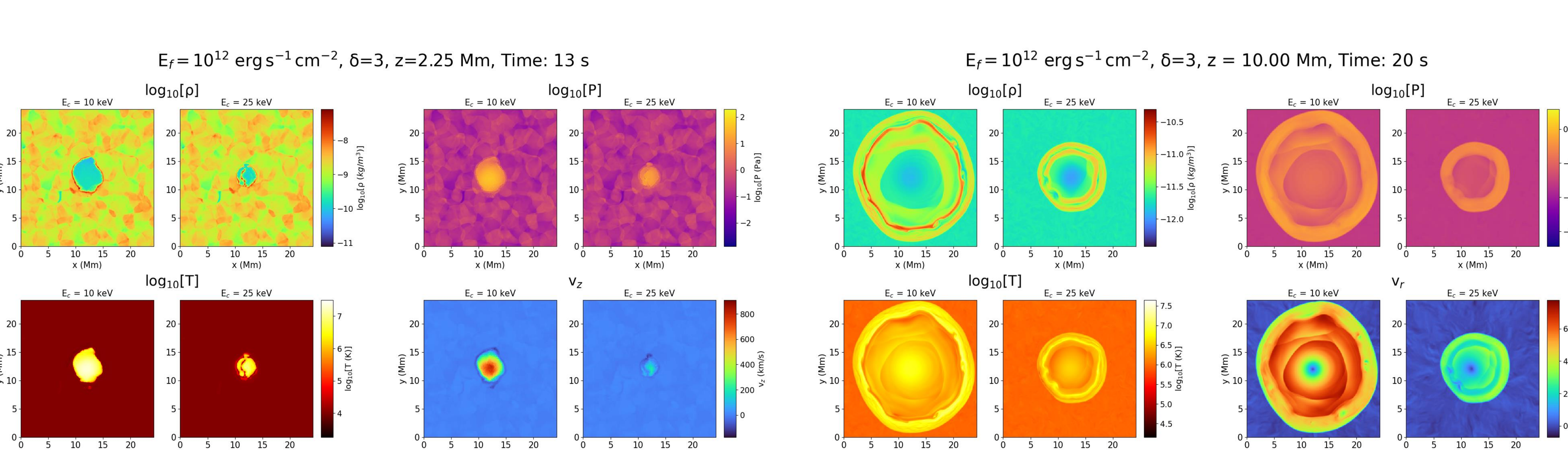
- Fast coronal shocks up to ~800 km/s and rapid lateral expansion.
- **Limited energy deposition below z = 1.25 Mm**

Effect of low-energy cutoff (Ec):

- Lower Ec: A larger number of electrons results in stronger heating higher in the atmosphere and earlier, more intense coronal shocks.
- Higher Ec: Fewer, more energetic electrons result in deeper penetration, heating at slightly lower heights, slower onset, and more localized chromospheric structuring.

Even with high Ec beams, energy deposition remains too shallow to directly heat the photosphere.



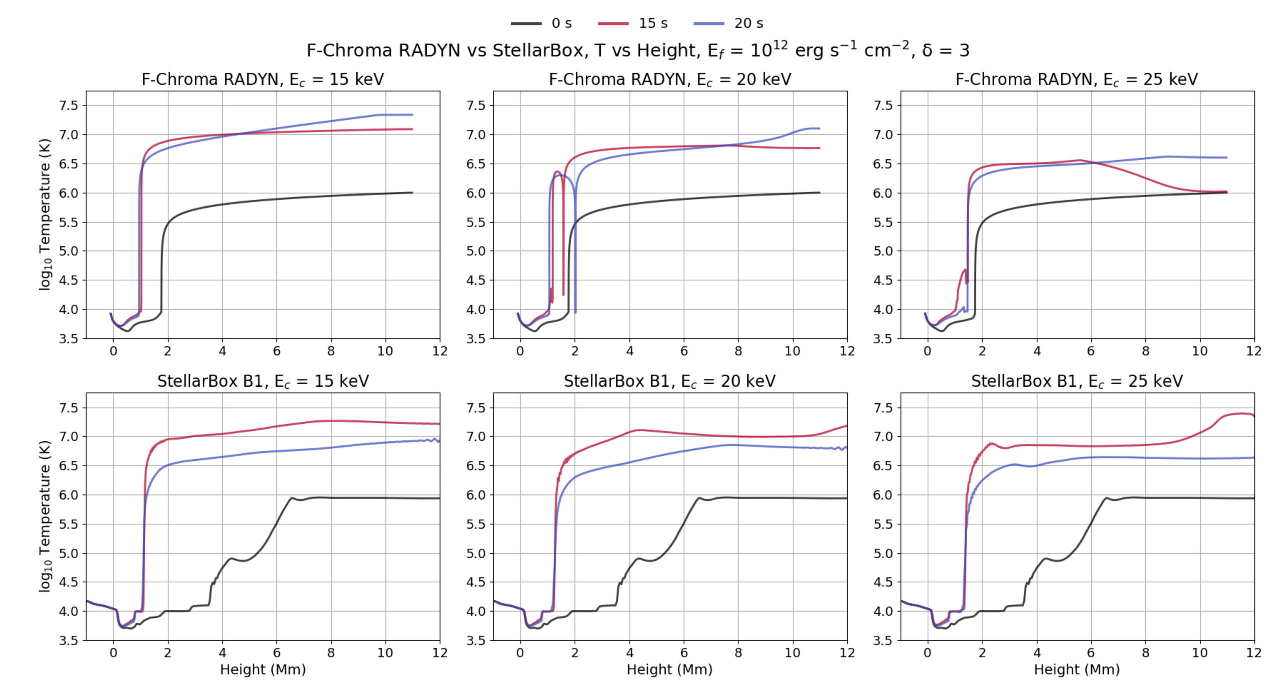


Comparison: 3D StellarBox vs 1D RADYN Models

Similarities: Same dependence on beam energy cutoff, similar heating depths, and chromospheric heating + condensation reproduced.

Differences: 3D models show fine-scale structuring, faster heating, higher peak temperatures, and rapid cooling due to lateral expansion and multidimensional energy transport.

Interpretation: Multidimensional transport significantly alters flare evolution, but not enough to deepen heating.



RH 1.5D: Observable Signatures

Continuum Emission:

- **Enhancement up to 2.5× pre-flare levels**
- Comparable to strong X-class WLFs
- Enhancement slightly stronger at higher Ec

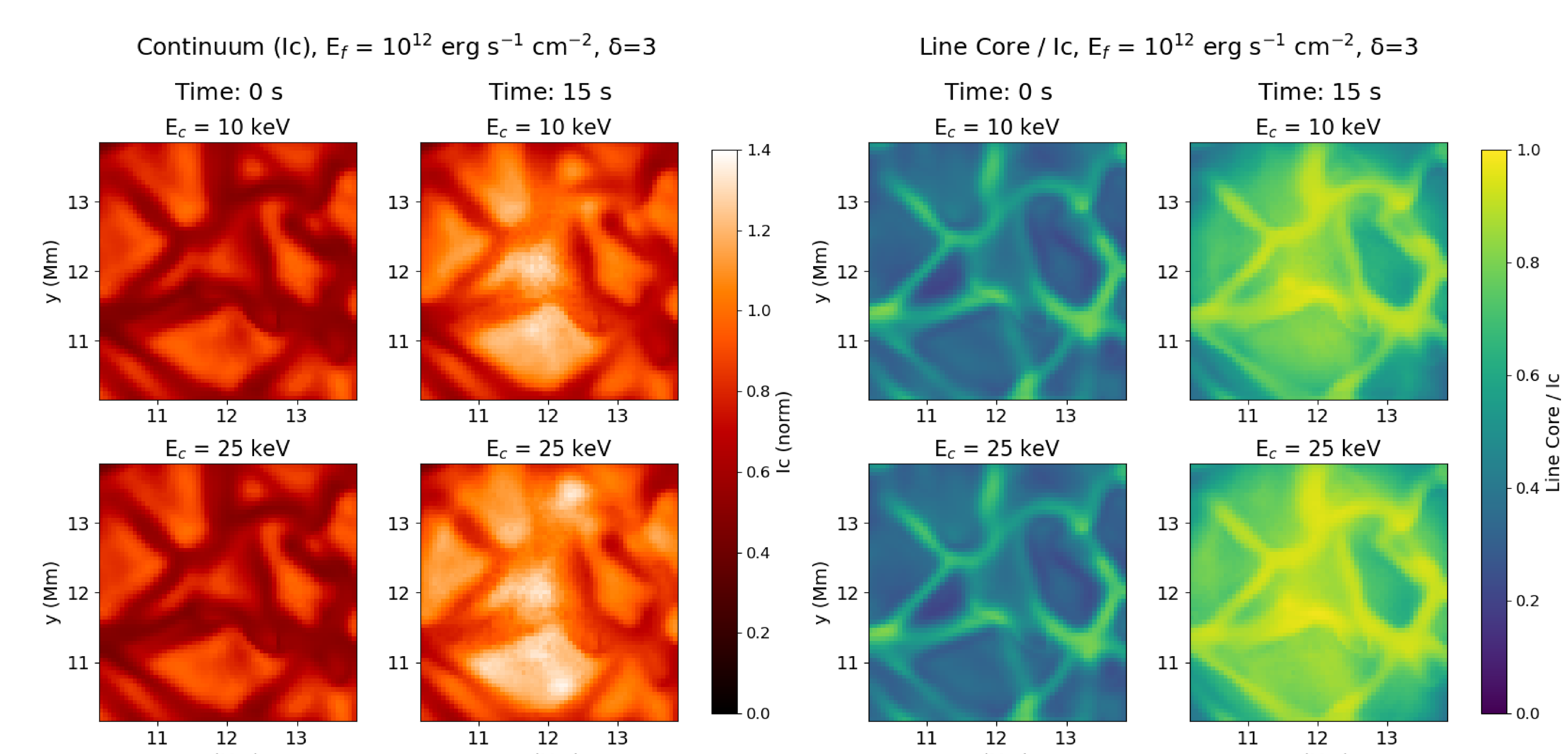
Fe I 6173 Å Line Core:

- **Line core reaches up to 97.8% of continuum intensity**
- Strong line-core brightening, however the line remains in absorption and does not reverse into emission as observed by HMI during some flares.
- Slightly stronger emission at higher Ec

Spatial Effects:

- Greatest continuum increase and line profiles closest to emission in / above **cooler regions** (intergranular lanes).

Implication: Electron beams can explain continuum brightening, but not the full line-core emission seen in observations.



Interpretation and Implications

Electron beams successfully reproduce:

- Strong continuum enhancements, dynamic chromospheric response

Electron beams do not fully reproduce:

- Deep photospheric heating, full Fe I line emission, strong helioseismic impulses

Likely missing physics:

- Deeper-penetrating particles (protons)
- Stronger magnetic fields (sunspot conditions)
- Field-aligned transport effects

Conclusions

3D radiative MHD models:

- Capture realistic structure and dynamics
- Improve over 1D models significantly

However:

- **Electron beams alone, under realistic 3D conditions, fail to reproduce the depth of heating required for observed white-light flare kernels and fully account for previously observed photospheric flare signatures.**

White-light flare kernels likely require:

- Additional energy transport mechanisms
- Realistic active-region environments

Future Work

Include:

- Proton and mixed particle beams
- Strong-field (sunspot) atmospheres
- Field-aligned transport physics

Goal: Fully explain white-light flare kernels and sunquake generation.