# Can Proton Beams Explain White-Light Flares and Sunquakes?

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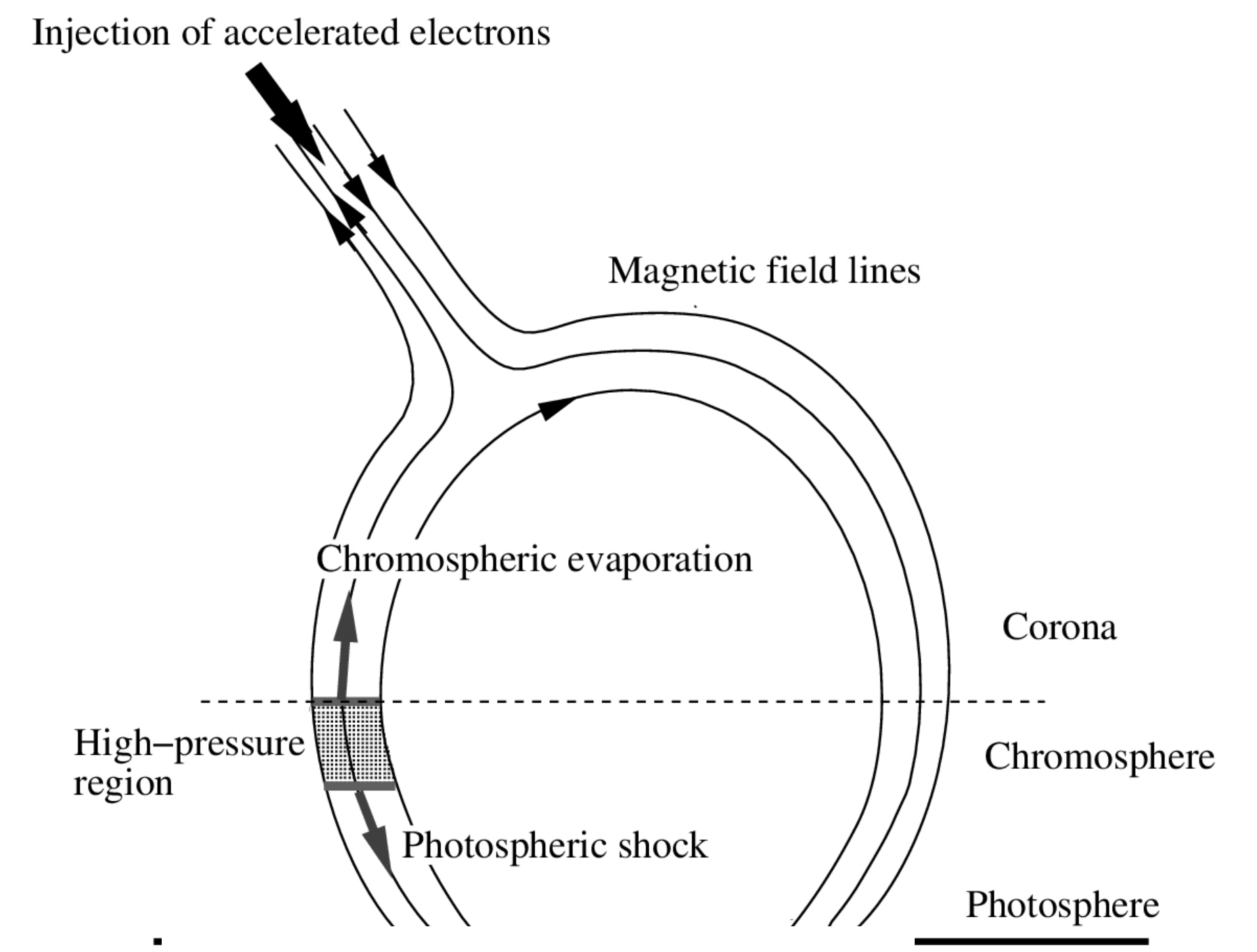
SDO/HMI observations reveal a class of solar flares with substantial energy and momentum impacts in the photosphere, resulting in white-light emission and helioseismic response (sunquakes). Previous radiative hydrodynamic modeling using the RADYN code showed that such impacts could not be explained in the framework of the standard flare model with electron beam heating. One of the possibilities to explain the observed white-light emission and sunquakes is to consider additional heating mechanisms involved in solar flares, for example, Alfvén wave heating and heating by the proton beams. In this work, we analyze the single-loop RADYN proton beam simulations for a wide set of beam parameters. Using the output of the RADYN models, we calculate synthetic HMI-line Stokes profiles and line-of-sight (LOS) observables as well as the 3D helioseismic response and compare them with the corresponding observed characteristics. The initial results show that the RADYN models with proton beam heating are substantially closer to the HMI observations than the standard electron-beam thick-target models.

## Motivation

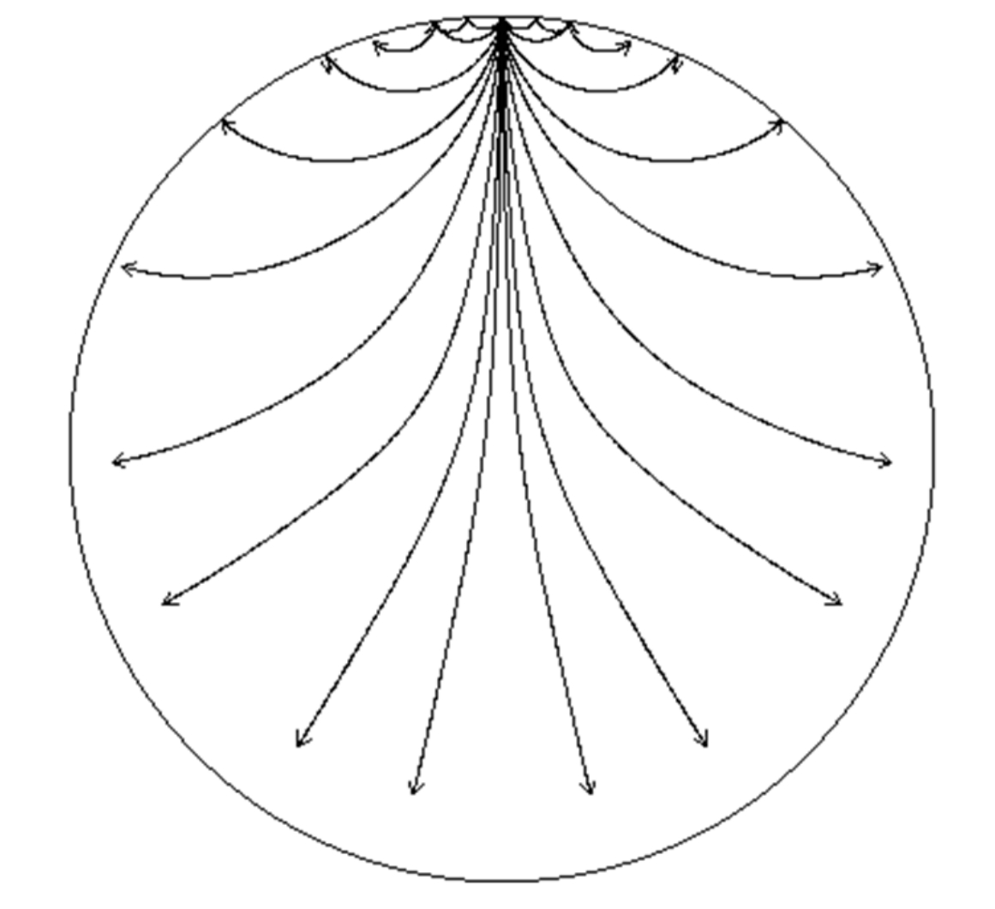
Sadykov et. al. (2020) performed modeling of the Fe I 6173 Å Stokes profiles and corresponding SDO/HMI LOS observables for the single-loop RADYN electron beam heating simulations available as a part of the F-CHROMA project. The continuum intensity observable enhancement was found to be just about 3%, and the Doppler shifts to be $\sim 0.4$ km/s, for the strongest considered run ($E_c$=25 keV, $\delta$=3, $E_{total}=10^{12}$ erg cm$^{-2}$). These perturbations cannot explain the continuum intensity enhancements (white light flares) and the helioseismic response signals (sunquakes) observed by SDO/HMI. These results put in question the standard thick-target flare model, which attempts to explain the observed phenomena by an impact of high-energy electrons.

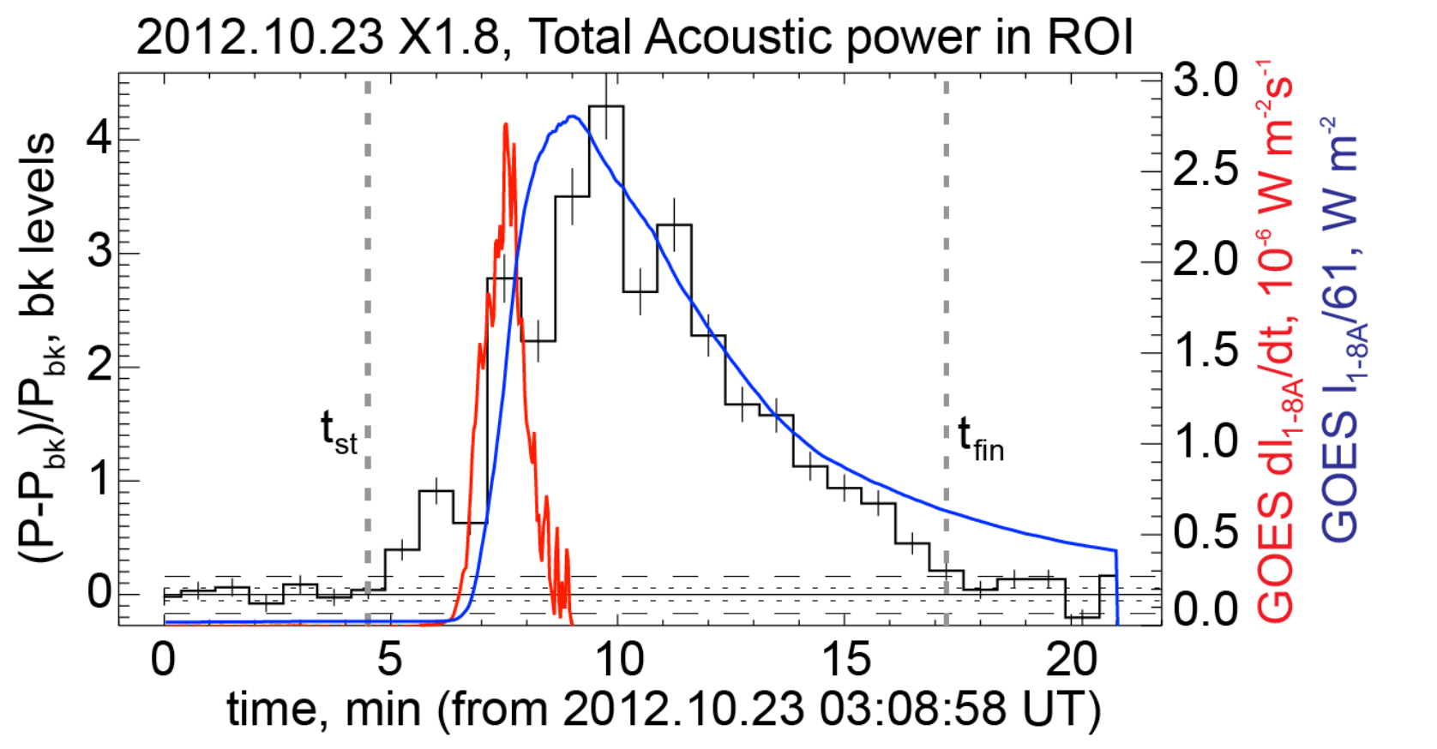
**In this work, we analyze the single-loop RADYN proton beam simulations of a wide set of beam parameters and impose the perturbations of these models into 3D acoustic models. Our goal is to answer the question, of *whether or not single-loos RADYN proton heating simulations can explain the emission observed in white-light flares and helioseismic signals detected in sunquakes.***

**Helioseismic responses to solar flares** ("sunquakes") occur due to localized force or/and momentum impacts observed during the flare impulsive phase in the lower atmosphere.
Such impacts may be caused by precipitation of high-energy particles, downward shocks, or magnetic Lorentz force. Understanding the mechanism of sunquakes is a key problem of flare energy release and transport.



**Flare impact**





The sunquake power correlates with the maximum value of the soft X-ray flux time derivative better than with the X-ray class, indicating that the sunquake mechanism is associated with high-energy particles (Sharykin and Kosovichev, 2020).

References

1. Sadykov, V.M., Kosovichev, A.G. Kitiashvili, I.N., and Kerr, G.S. 2020, Response of SDO/HMI Observables to Heating of the Solar Atmosphere by Precipitating High-energy Electrons, ApJ, 893(1):24
2. Sharykin, I.N, and Kosovichev, A.G., 2020, Sunquakes of Solar Cycle 24, ApJ, 895(1): 76.
3. Stefan, J.T., and Kosovichev, A.G. 2020, Estimation of Key Sunquake Parameters through Hydrodynamic Modeling and Cross-correlation Analysis, ApJ, 895(1): 65
4. Allred, J.C., Alaoui, M., Kowalski, A.F., and Kerr, Graham S., 2020, Modeling the Transport of Nonthermal Particles in Flares Using Fokker-Planck Kinetic Theory, ApJ, 902(1): 16

## RADYN Flare Hydrodynamics for Proton Beams: Photospheric Impact

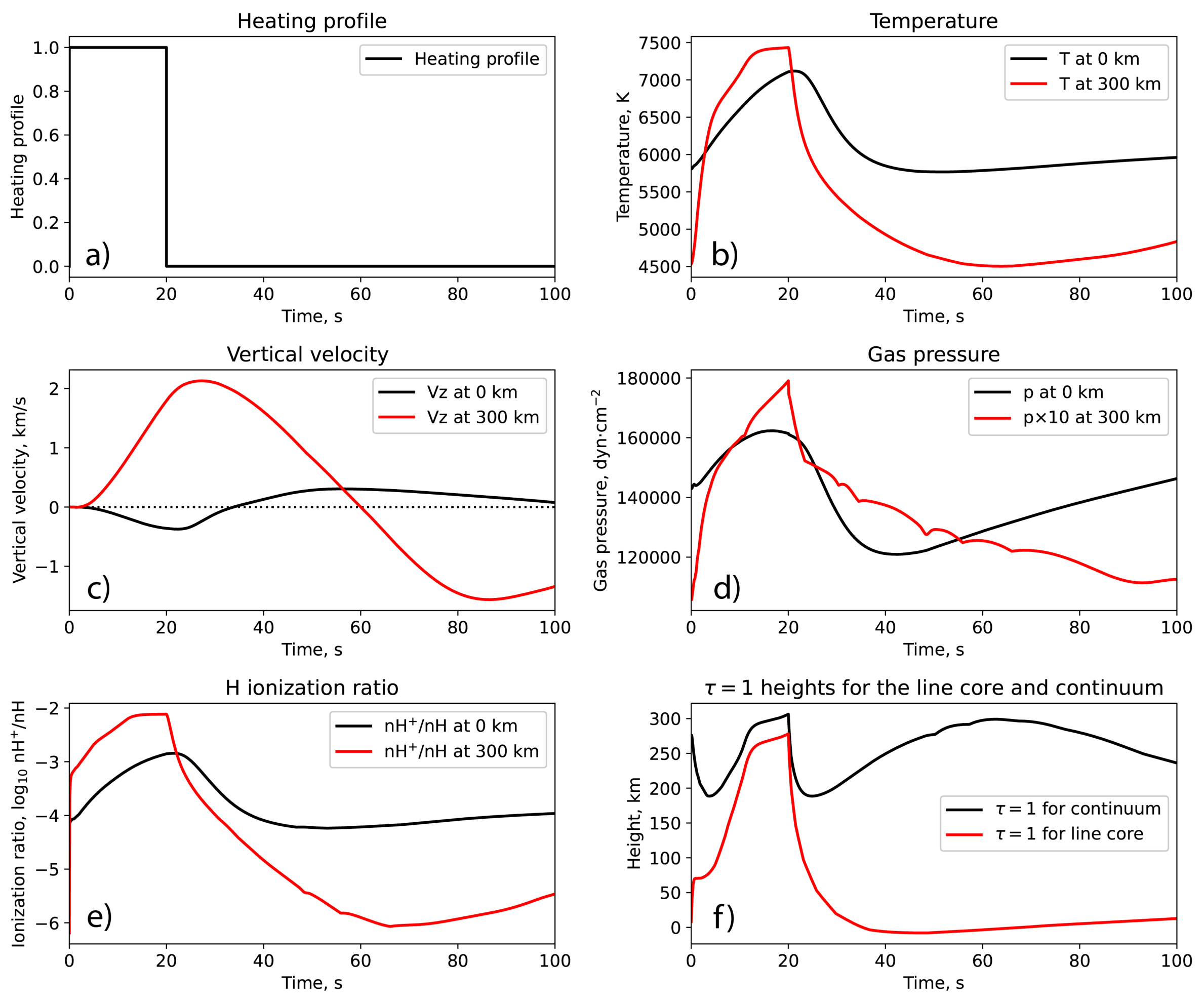
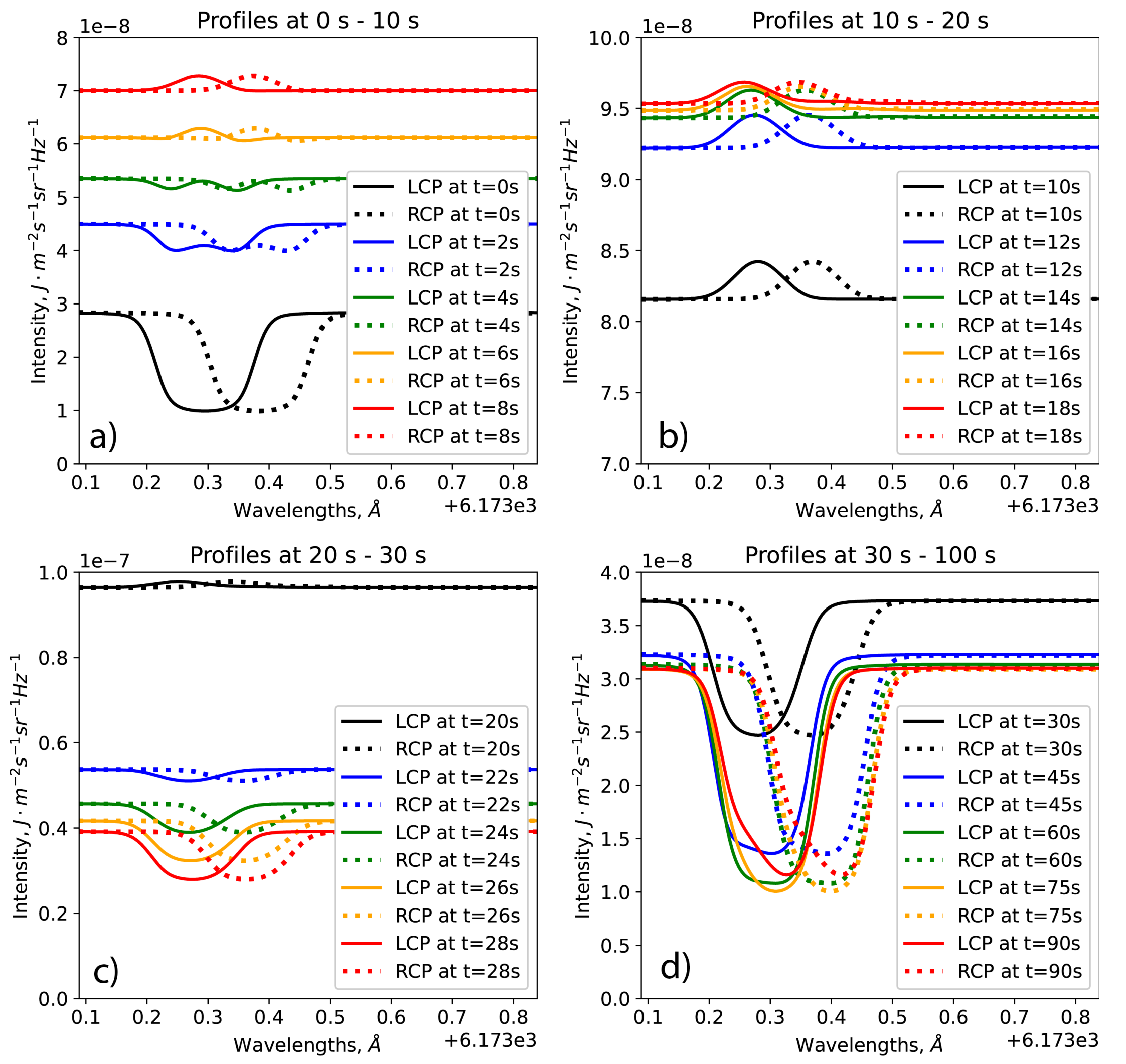


Illustration of the normalized proton energy flux time profile (a), and temperature (b), vertical velocity (c), gas pressure (d), hydrogen ionization degree (e) time profiles at the 0 km (black solid curve), and 300 km heights (red solid curve) for the RADYN proton beam heating model with the low-energy cutoff $E_c$ =1000 keV, spectral index $\delta$=3, and total energy flux $E_t=10^{12}$ erg cm$^{-2}$. The heights for the Fe I 6173 Å line core and continuum are presented in panel (f).

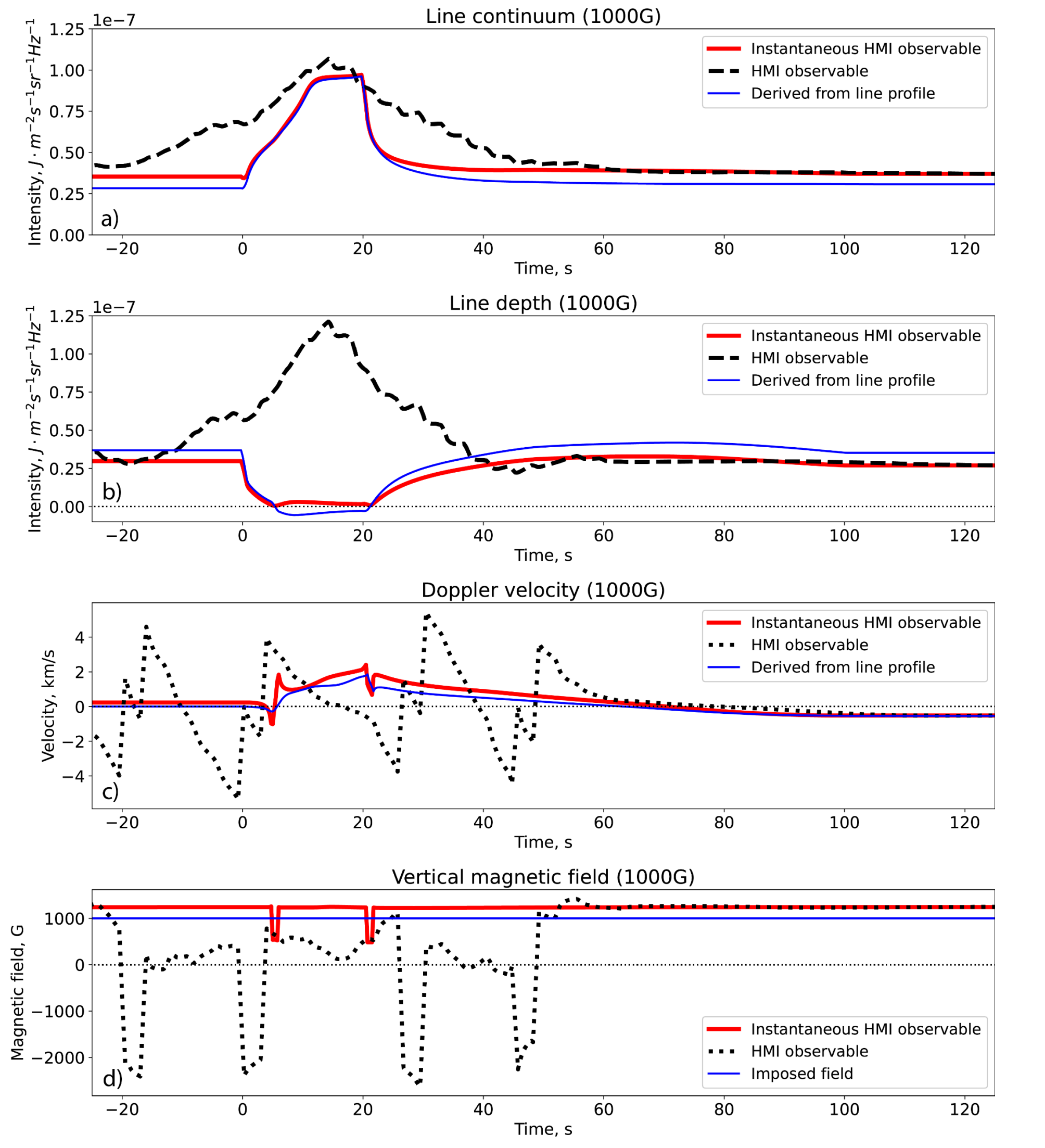
## Effects of Proton Beam on Fe I 6137 A line

RADYN proton run 1000keV.3.F12.1000G



Fe I 6173 Å Left Circular Polarization (LCP) (solid) and Right Circular Polarization (RCP) (dashed) line profiles for the RADYN proton beam heating model with $E_c$ =1000 keV, $\delta$=3, $E_t=10^{12}$ erg cm$^{-2}$ and the vertical uniform 1000 G magnetic field at: 0-10 s (a), 10-20 s (b), 20-30 s (c), and 30-100 s (d). The times at which the profiles are sampled are coded by color.

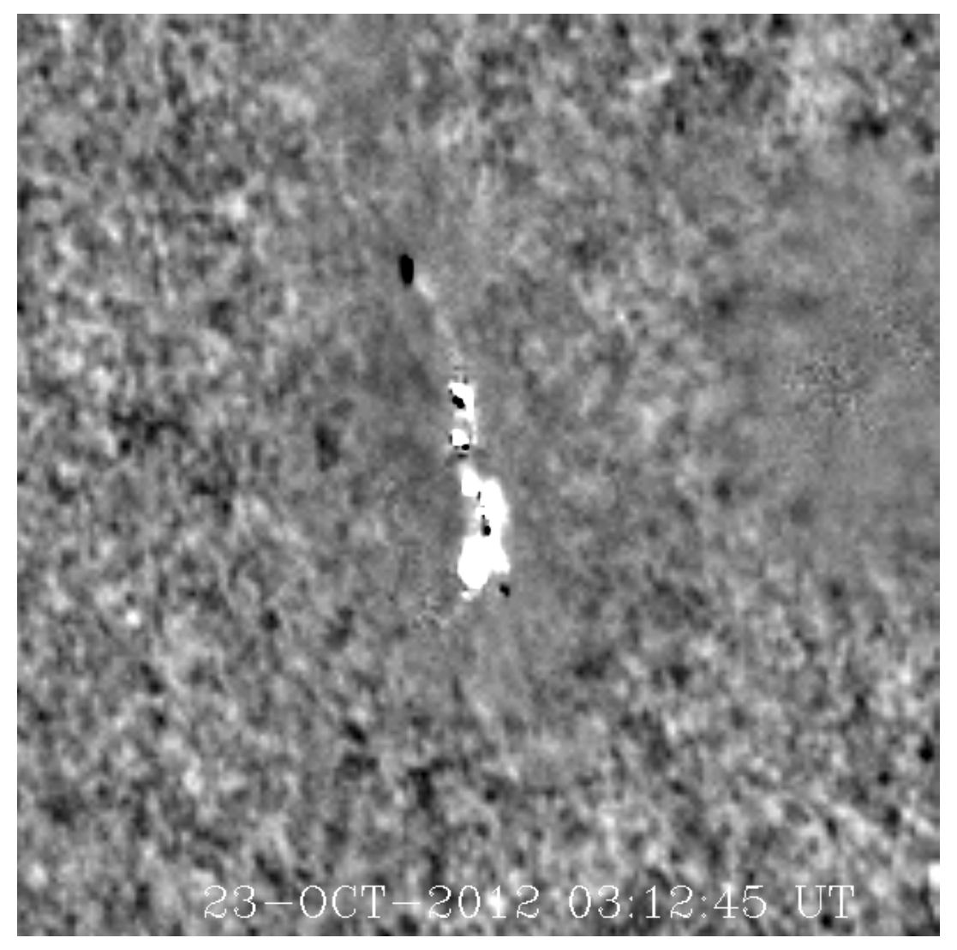
## SDO/HMI Synthetic Observables



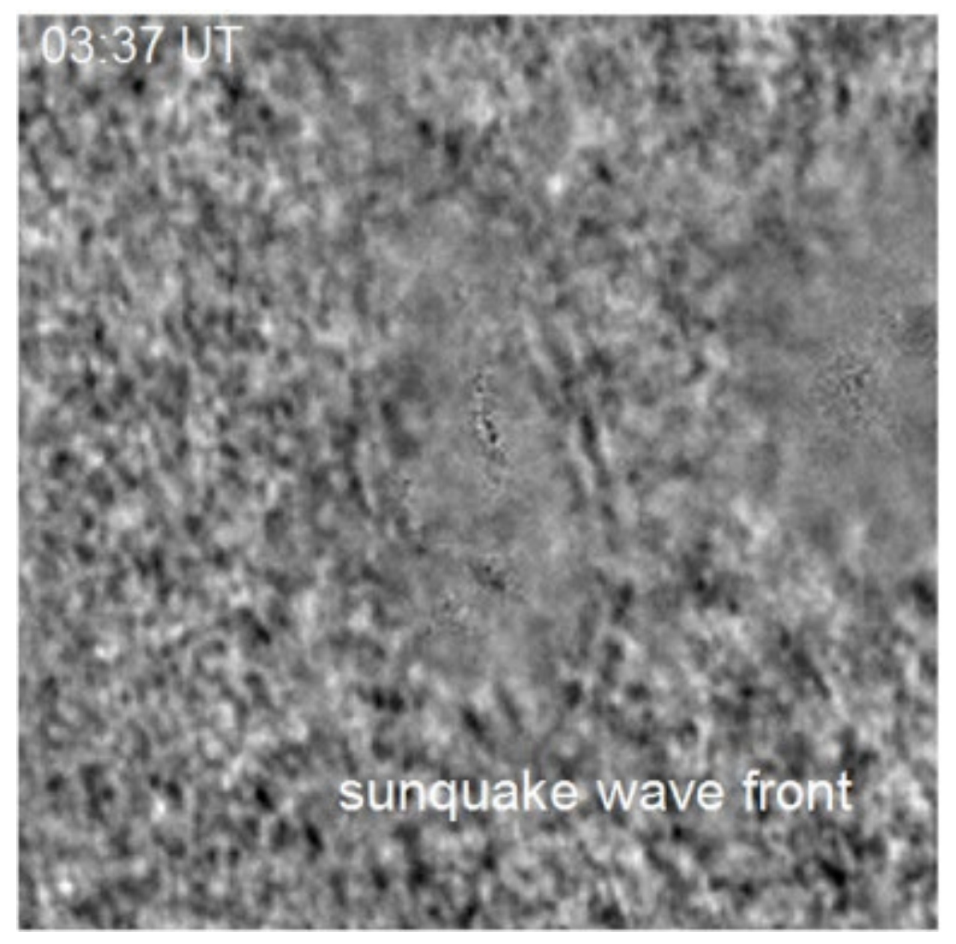
Fe I 6173 Å line parameters and the corresponding simulated SDO/HMI observables for RADYN proton beam heating model with $E_c$ =1000 keV, $\delta$=3, $E_t=10^{12}$ erg cm$^{-2}$ for the vertical uniform 1000 G magnetic field. The blue curves correspond to the measurements obtained from the native line profiles. The red solid curves show "instantaneous" observables obtained with the HMI algorithm applied to the line profile instantaneously. The black dashed curves show the observables obtained with the HMI algorithm applied with the actual observing sequence timing centered at the reference time. The black dashed horizontal lines in panels (c) and (d) mark the zero level of the observables.

## SDO/HMI Observations: X1.8 flare

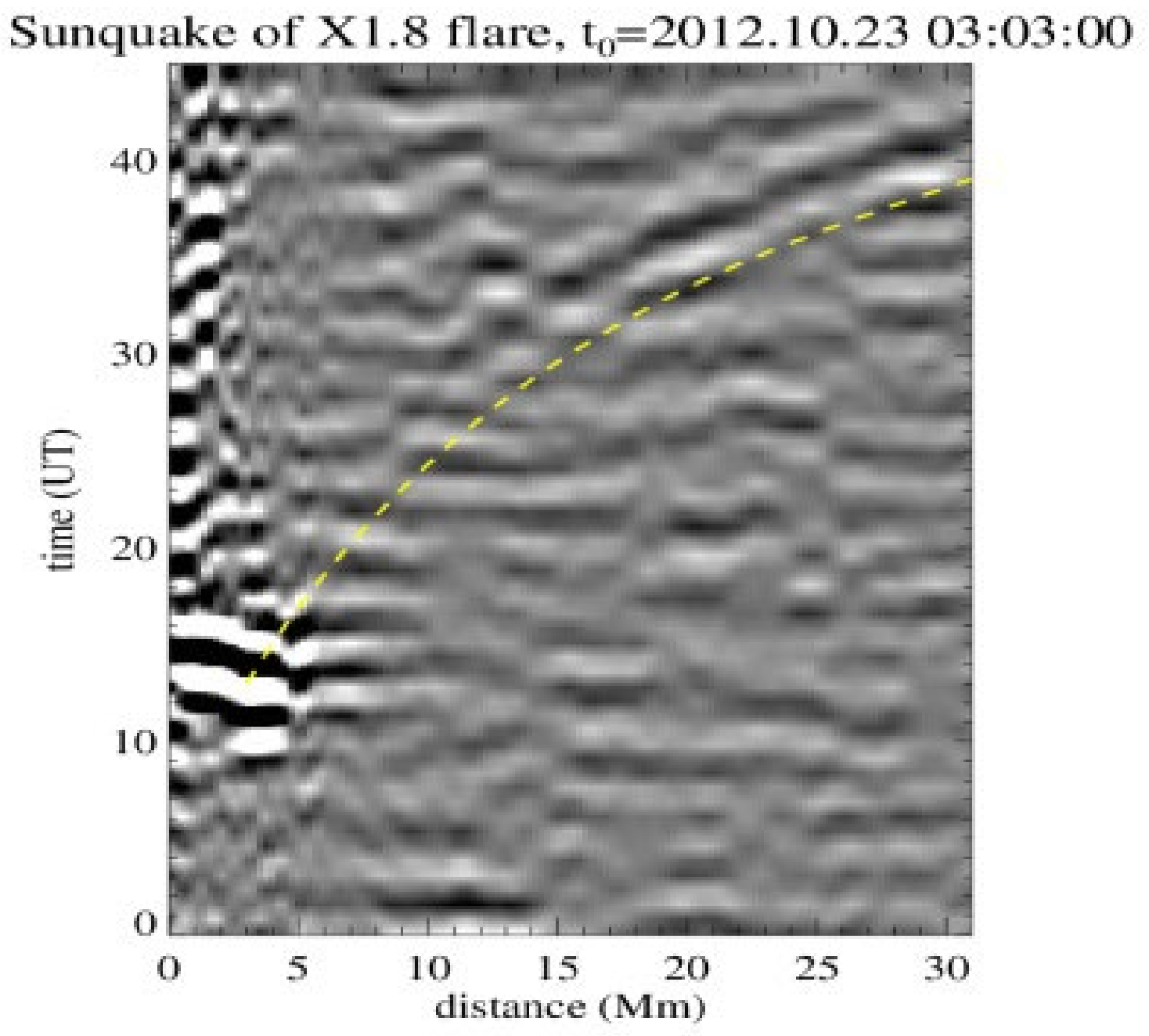
Doppler velocity perturbations during the flare initial impact at the photosphere reach 10 km/s.



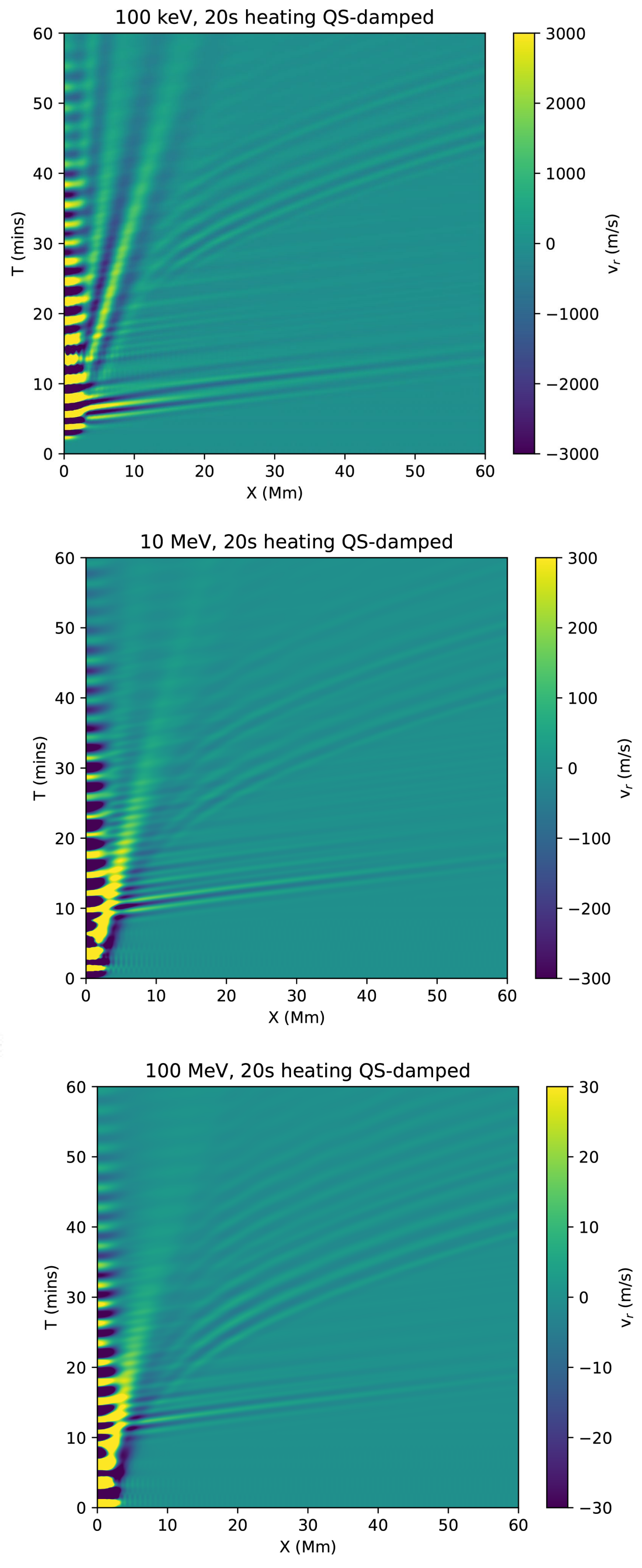
Doppler velocity perturbations reveal expanding wave ripples representing packets of acoustic waves that traveled through the solar interior and emerged on the surface.
The wave amplitude is about 300 m/s.



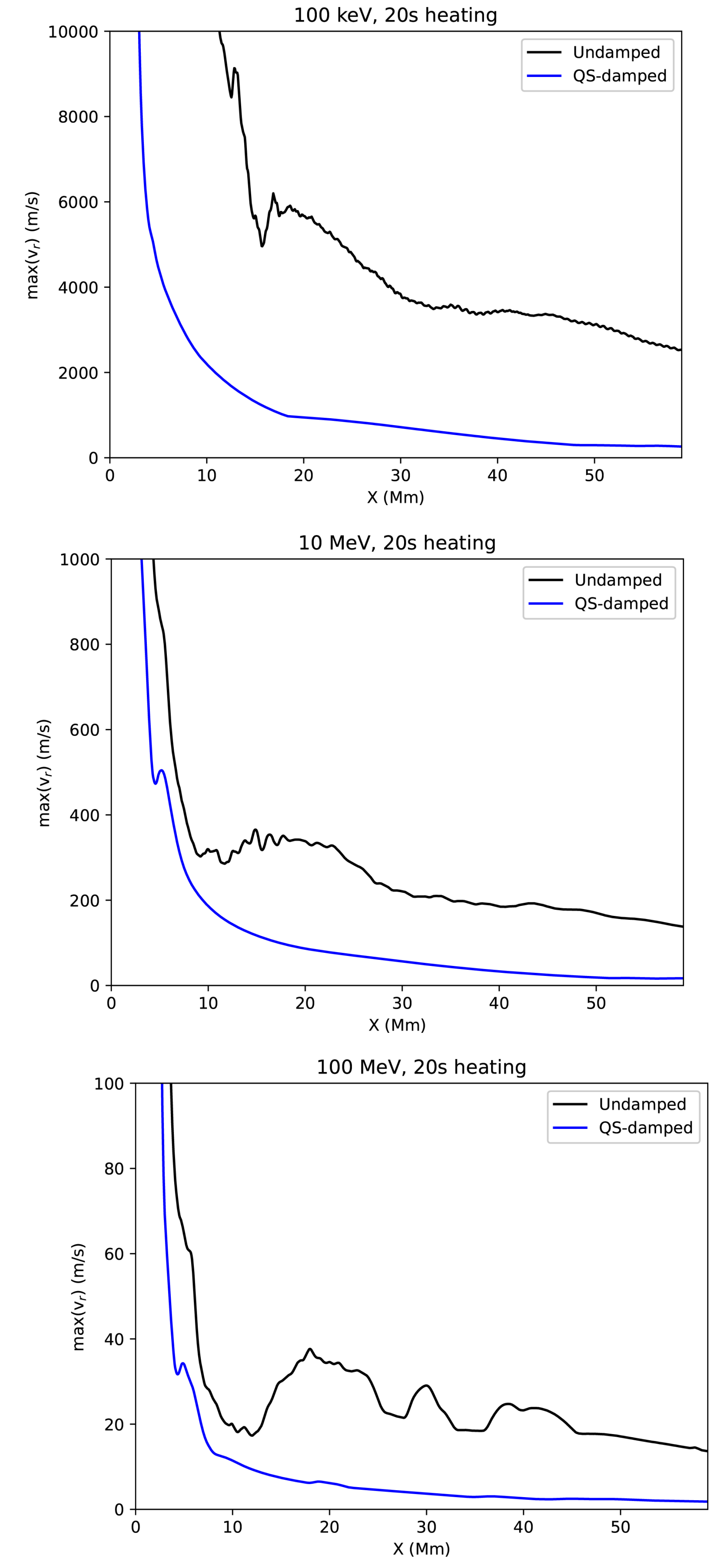
Time-distance diagram of the sunquake Doppler velocity signal observed by SDO/HMI. Strong perturbations around t=10-20 min are caused by the initial photospheric impact. The inclined curved ripples represent the sunquake. The dashed line shows the theoretical ray path of helioseismic waves,.



## Sunquake Models for Proton Beams: Theoretical Time-distance Diagrams

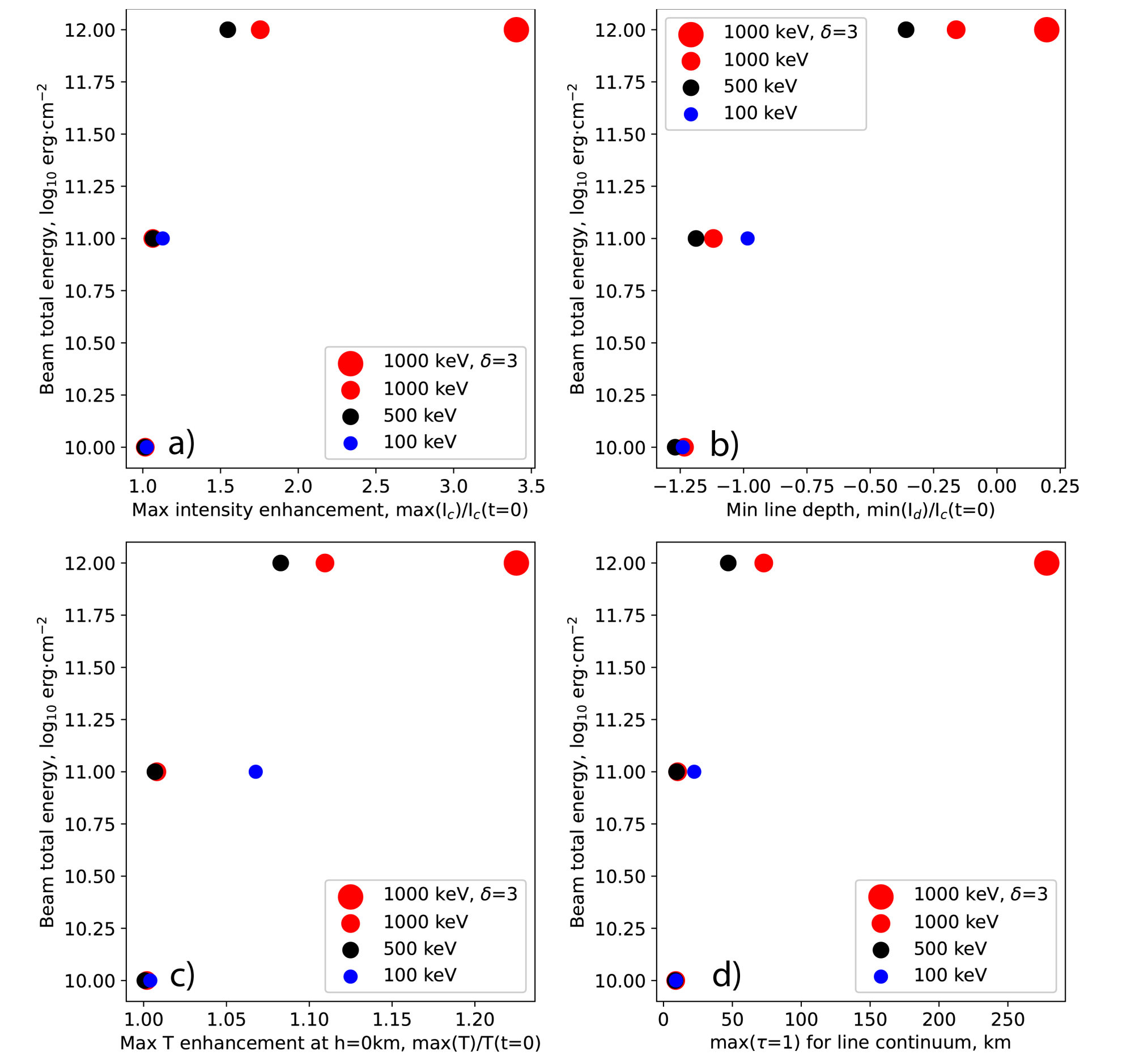


## Maximum Velocity Amplitude of Sunquakes vs Distance from Proton Beam Impact



The helioseismic modeling is performed for direct proton-beam heating sources using the sunquake modeling code of Stefan and Kosovichev (2020) and the Fokker-Planck Kinetic Theory code of Allred et al. (2020). The horizontal size of the proton beam is 1000 km. The helioseismic model includes the solar interior, atmosphere, and corona. The damping of helioseismic waves is modeled using the observed p-mode line widths.

## Maximum Photospheric Effects of Proton Beams



The maximum intensity enhancement (a), minimal values of the Fe I 6173 Å line depth (b), the maximum temperature enhancement at h=0 km (c), and the maximum height for the line continuum as the function of the total deposited energy in the RADYN proton beam runs. The low-energy cutoffs are coded by color. The spectral index is $\delta$=5 unless mentioned otherwise.

## Conclusions

- **The inclusion of proton beams in the RADYN radiative hydrodynamic flare model allows us to explain the white-light emission and strong variations of other photospheric properties (the Doppler shift, spectral line depth, and magnetic field), observed by the SDO HMI instrument during the impulsive phase of solar flares.**
- **In addition, the proton beams penetrating into the deep photospheric and subphotospheric layers can deposit the energy sufficient for generating the helioseismic response – sunquakes.**