



Energetics and Emission in a Simulated Solar Flare Initialized by a Non-force-free Magnetic Field

W. Bate¹ , M. Gordovskyy¹ , A. Prasad^{2,3,4} , A. S. Brun⁵ , A. Strugarek⁵ , M. V. Sieyra⁵ , P. K. Browning⁶ ,
S. Inoue⁷ , K. Matsumoto⁷ , and A. Roddanavar⁷

¹ Department of Physics, Astronomy & Mathematics, University of Hertfordshire, Hatfield, AL10 9AB, UK; w.bate@herts.ac.uk

² Statkraft AS, Lysaker, Norway

³ Roseland Centre for Solar Physics, University of Oslo, Blindern Postboks 1029, 0315 Oslo, Norway

⁴ Institute of Theoretical Astrophysics, University of Oslo, Blindern Postboks 1029, 0315 Oslo, Norway

⁵ Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191, Gif-sur-Yvette, France

⁶ Jodrell Bank Centre for Astrophysics, University of Manchester, Manchester, M13 9PL, UK

⁷ Center for Solar-Terrestrial Research, New Jersey Institute of Technology, University Heights, Newark, NJ 07102-1982, USA

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Abstract

Solar flare simulations are commonly initialised using nonlinear force-free field (NLFF) extrapolations derived from photospheric vector magnetograms. However, the force-free assumption neglects plasma forces and may limit the available free magnetic energy. In this work, we perform a controlled comparison of two three-dimensional resistive magnetohydrodynamic simulations of the X2.1-class flare that occurred on 2011 September 6 in NOAA Active Region 11283. The simulations differ only in their initial magnetic configuration: one is based on a conventional NLFF extrapolation, while the other employs a non-force-free extrapolation. Both models are evolved in an identical stratified atmosphere using the same numerical framework, enabling direct assessment of how the initial magnetic assumptions influence flare dynamics and energetics. We find that the non-force-free model undergoes more extensive magnetic restructuring and releases approximately twice as much magnetic energy ($\approx 4.4 \times 10^{31}$ erg) as the NLFF case ($\approx 2.3 \times 10^{31}$ erg), bringing the energy budget into closer agreement with expectations for X-class flares. Synthetic extreme-ultraviolet emission in the 94 Å channel is computed for both simulations and compared with observations from the Solar Dynamics Observatory. The non-force-free model produces a brighter and more spatially extended emission structure that more closely resembles the observed flare morphology and light curve. These results demonstrate that assumptions made in constructing the preflare coronal magnetic field can significantly affect flare energetics and observable signatures and suggest that non-force-free extrapolations provide a promising pathway toward more realistic data-constrained flare modelling.

Unified Astronomy Thesaurus concepts: [Solar atmosphere \(1477\)](#); [Solar flares \(1496\)](#); [Solar corona \(1483\)](#)

Materials only available in the [online version of record](#): animation

1. Introduction

Solar flares are manifestations of rapid magnetic energy release in the solar corona. They are accompanied by strong plasma heating, bulk flows, and intense radiation across the electromagnetic spectrum. Extreme-ultraviolet (EUV) and X-ray observations show that flaring coronal plasma is structured by the magnetic field and evolves rapidly during the energy release process, reflecting both the preflare magnetic configuration and its subsequent reconfiguration through magnetic reconnection. How the coronal magnetic field stores energy and how this energy is converted into thermal and nonthermal plasma during flares remain some of the central problems in solar physics.

Due to the fact that direct measurements of the coronal magnetic field are limited, numerical modeling plays a crucial role in interpreting flare observations (T. Wiegelmann & T. Sakurai 2012). A common approach in flare modeling is to initialize magnetohydrodynamic (MHD) simulations using magnetic field extrapolations based on photospheric vector

magnetograms. In particular, nonlinear force-free field (NLFF) extrapolations have been widely used in previous studies, motivated by the low plasma beta of the preflare corona and the assumption that Lorentz forces are small prior to flare onset (G. A. Gary 2001). MHD models based on NLFF initial conditions have successfully reproduced a range of observed flare-related phenomena, including the large-scale evolution of coronal loops, current sheet formation, and locations of energy release (see S. Toriumi & H. Wang 2019 for a comprehensive review).

However, the force-free assumption is not strictly valid in the photosphere where the initial magnetograms are taken from. This is due to the fact that there is a nonnegligible Lorentz force in the photosphere as plasma beta is on the order of unity (G. A. Gary 2001). This requires significant preprocessing of the original photospheric magnetogram before performing the extrapolation, approximating the chromospheric magnetic field (C. J. Schrijver et al. 2008; T. Wiegelmann et al. 2008). This raises the question of how sensitive flare simulations and their observational signatures are to the choice of magnetic field model used to initialize the MHD calculations.

A number of recent studies have demonstrated the power of data-constrained and data-driven MHD simulations in



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reproducing observed flare dynamics and energetics. For example, M. Gordovskyy et al. (2020) performed three-dimensional MHD simulations of an X-class flare initialized with an NLFF extrapolation derived from Helioseismic and Magnetic Imager (HMI; J. Schou et al. 2012) vector magnetograms, showing that the subsequent evolution naturally produced the formation of current sheets, magnetic reconnection, and large-scale restructuring consistent with EUV and X-ray observations. They highlighted, however, that NLFF-based models can struggle to supply sufficient free magnetic energy to fully account for the observed flare energy budget. Extending this approach, M. Gordovskyy et al. (2023) incorporated more realistic thermodynamics and particle acceleration diagnostics, enabling direct comparison of synthetic emission and nonthermal signatures with observations and further emphasizing the sensitivity of flare evolution to the preeruptive magnetic configuration. Similarly, S. Masson et al. (2017) modeled a confined flare using a magnetofrictional relaxation followed by full MHD evolution, successfully reproducing the development of quasi-separatrix layers, slipping reconnection, and flare ribbon morphology. Together, these works illustrate that while NLFF-initialized MHD models can capture many key aspects of flare topology and reconnection dynamics, the detailed energy release, emission structure, and reconnection geometry depend critically on the assumed preflare magnetic field, motivating continued investigation of alternative extrapolation strategies such as the non-force-free approach adopted within this work.

In addition to the choice of magnetic field extrapolation, the thermodynamic structure of the background atmosphere plays a significant role in flare simulations. Early three-dimensional MHD studies of eruptive events often adopted uniform density and pressure profiles or zero-beta approximations to simplify the dynamics and isolate magnetic effects (e.g., Z. Mikic & A. N. McClymont 1994). However, the solar corona is strongly stratified under gravity, with density and pressure decreasing exponentially with height above the photosphere (e.g., G. A. Gary 2001). More recent flare and flux-rope simulations have therefore incorporated gravitationally stratified atmospheres to better capture the variation of Alfvén speed, plasma beta, and energy transport with height (e.g., M. Gordovskyy et al. 2014). A stratified atmosphere provides a more realistic distribution of mass loading along magnetic field lines, influences the onset and growth of instabilities, and affects the partition of released magnetic energy into kinetic and thermal components (M. V. Sieyra et al. 2026). It also enables more meaningful forward modeling of optically thin EUV and X-ray emission, since the emissivity depends sensitively on the local density squared. Consequently, including stratification is important not only for reproducing the large-scale magnetic evolution but also for obtaining quantitatively reliable synthetic observables and flare energetics.

Alternative approaches have been developed that relax the force-free constraint and allow for magnetic field configurations that are not in force balance, incorporating plasma forces self-consistently from the outset (Q. Hu & B. Dasgupta 2008; Q. Hu et al. 2008, 2010). These non-force-free models aim to provide a more realistic representation of the low-coronal magnetic field and plasma state, potentially leading to different flare dynamics and observable signatures. Recently, these non-force-free extrapolations have been used to initialize simulations leading to solar flares, coronal jets, and coronal

dimmings (A. Prasad et al. 2018, 2020, 2023; S. S. Nayak et al. 2019; S. Kumar et al. 2022; M. V. Sieyra et al. 2026). They also offer an opportunity to assess the limitations of traditional force-free extrapolations and to evaluate whether a more complete treatment of the preflare coronal environment improves agreement with observations.

In this study, we directly compare two three-dimensional MHD models of the same solar flare that differ only in their initial magnetic field configuration. The first model is initialized using a standard NLFF extrapolation, representative of the approach commonly adopted in previous flare modeling studies. The second model employs a newly developed non-force-free magnetic field model, which allows for finite Lorentz forces and includes plasma pressure and gravity in the initial equilibrium. Both models are evolved using the same MHD framework, enabling a controlled comparison of their magnetic evolution, plasma heating, and resulting coronal emission.

To evaluate the realism of the two modeling approaches, we compute synthetic EUV emission in the Atmospheric Imaging Assembly (AIA; J. R. Lemen et al. 2012) 94 Å channel from each simulation and compare it with observations of the actual flare. The 94 Å channel is particularly sensitive to hot flare plasma and provides a stringent test of the models' ability to reproduce the spatial structure and temporal evolution of flare-heated coronal loops. By comparing synthetic and observed EUV emission, we assess how differences in the initial magnetic field assumptions propagate into observable consequences during the flare.

The paper is organized as follows: Section 2 details the observations and extrapolations used within this work, including the NLFF extrapolation (Section 2.1), non-force-free extrapolation (Section 2.2), and the production of synthetic AIA observations (Section 2.3). Section 3 details the simulation setup and comparisons between the two initial fields, Section 4 presents the results and analysis, and Section 5 details the authors' conclusions.

2. Observations and Extrapolations

For this work, observations of the X2.1-class flare on 2011 September 6 in Active Region AR11283 were utilized. These observations were taken with the Solar Dynamics Observatory's (SDO; W. D. Pesnell et al. 2012) HMI (J. Schou et al. 2012) and AIA (J. R. Lemen et al. 2012). This flare reached peak brightness at 22:21 UT and a preflare HMI magnetogram was used, taken at 20:48 UT. A section of this HMI magnetogram was taken using the Space-weather HMI Active Region Patch (SHARP; M. G. Bobra et al. 2014) for SHARP 833 (associated with AR11283). The cylindrical equal area projected version of this vector magnetogram was used to perform the magnetic field extrapolations described below. Further, AIA observations from the 94 Å channel are taken due to the intensity of this flare and the fact that the peak of the 94 Å response function is at the highest temperature of any of the AIA channels (Table 1 of J. R. Lemen et al. 2012).

2.1. NLFF Extrapolation

The NLFF extrapolation was obtained using the methods described in S. Inoue et al. (2014). This method is based on magnetic relaxation, developed by A. N. McClymont & Z. Mikic (1994) and Z. Mikic & A. N. McClymont (1994), with an

additional algorithm to prevent deviation from the $\nabla \cdot \mathbf{B} = 0$ condition. First, the zero-beta (without gas pressure and gravity) MHD equations are considered. Therefore, the following equations are numerically solved:

$$\frac{\partial \mathbf{v}}{\partial t} = -(\mathbf{v} \cdot \nabla) \mathbf{v} + \frac{1}{\rho} (\mathbf{J} \times \mathbf{B}) + \nu \nabla^2 \mathbf{v}, \quad (1)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times ((\mathbf{v} \times \mathbf{B}) - \eta \mathbf{J}) - \nabla \phi, \quad (2)$$

$$\mathbf{J} = \nabla \times \mathbf{B}, \quad (3)$$

where $\mathbf{B}$ is the magnetic flux density, $\mathbf{v}$ is the velocity, $\mathbf{J}$ is the electric current density, ρ is the pseudodensity, ϕ is the initial potential field, ν is the viscosity, and η is the resistivity. The pseudodensity is set as proportional to $|\mathbf{B}|$ in order to make the Alfvén speed equal everywhere, easing the relaxation process.

The additional step to prevent deviations from $\nabla \cdot \mathbf{B} = 0$ was first introduced by A. Dedner et al. (2002) and is as follows:

$$\frac{\partial \phi}{\partial t} + c_h^2 (\nabla \cdot \mathbf{B}) = -\frac{c_h^2}{c_p^2} \phi, \quad (4)$$

where the combination of Equations (2) and (4) leads to

$$\frac{\partial^2 (\nabla \cdot \mathbf{B})}{\partial t^2} + \frac{c_h^2}{c_p^2} \frac{\partial (\nabla \cdot \mathbf{B})}{\partial t} = c_h^2 \nabla^2 (\nabla \cdot \mathbf{B}), \quad (5)$$

illustrating the propagating and diffusing nature of numerical errors relating to $\nabla \cdot \mathbf{B}$, where c_h and c_p correspond to the advection and diffusion coefficients, respectively. Following these equations and boundary conditions based on the observed vector magnetogram at the lower boundary, and rigid wall conditions for the others, the magnetic field is allowed to relax into a force-free state.

2.2. Non-force-free Extrapolation

The non-force-free extrapolation was calculated using the method developed by Q. Hu & B. Dasgupta (2008) and Q. Hu et al. (2008, 2010). This approach combines three linear force-free fields as

$$\mathbf{B} = \mathbf{B}_1 + \mathbf{B}_2 + \mathbf{B}_3 \quad ; \quad \nabla \times \mathbf{B}_i = \alpha_i \mathbf{B}_i, \quad (6)$$

with $i = 1, 2, 3$, and α_i being the corresponding constant for each linear force-free field.

$\mathbf{B}_2$ is chosen as a potential field, so $\alpha_2 = 0$, and we set $\alpha_1 \neq \alpha_3$. An optimal set of α_1 and α_3 is found by minimizing the difference between the observed and calculated transverse fields on the photospheric boundary ($\mathbf{B}_t$ and $\mathbf{b}_t$, respectively). The metric used to assess this is described in A. Prasad et al. (2018) and is as follows:

$$E_n = \left(\sum_{i=1}^M |\mathbf{B}_{t,i} - \mathbf{b}_{t,i}| \times |\mathbf{B}_{t,i}| \right) / \left(\sum_{i=1}^M |\mathbf{B}_{t,i}|^2 \right), \quad (7)$$

where M is the number of points in the photospheric plane. The denominator, normalizing by the observed transverse magnetic field, ensures that contribution from weak fields is minimized (Q. Hu & B. Dasgupta 2008; Q. Hu et al. 2010).

This extrapolated field, $\mathbf{B}$, is the solution of the following equation:

$$\nabla \times \nabla \times \nabla \times \mathbf{B} + a_1 \nabla \times \nabla \times \mathbf{B} + b_1 \nabla \times \mathbf{B} = 0, \quad (8)$$

which is a higher-curl equation with a_1 and b_1 as constants. This is derived by applying the principle of minimum dissipation rate, the process for which is described by R. Bhattacharyya & M. S. Janaki (2004), and Equation (8) results from taking the curl of both sides of their Equation (12). Equation (8) contains a second-order derivative at $z = 0$, which would require magnetograms at two different z -values. In reality, only one photospheric magnetogram at a single height is typically available due to the use of, e.g., HMI. In order to circumvent this, an iterative approach, described fully by Q. Hu et al. (2010), is used to minimize the deviation between the observed and the calculated transverse magnetic field (measured by E_n in Equation (7)).

2.3. Synthetic AIA Observations

AIA (J. R. Lemen et al. 2012) on board SDO (W. D. Pesnell et al. 2012) has proved to be an invaluable tool for modern solar physics studies since its launch in 2010. This is in part thanks to its 1.5'' spatial resolution and 12 s cadence with data taken over more than one decade. Further, the range of EUV wavelengths available allows for the examination of a wide range of plasma temperatures. The wavelength with the highest characteristic $\log(T)$, with a value of 6.8, is the 94 Å channel, primarily focused on the Fe XVIII ion. This is described as sampling the “flaring corona” and is thus particularly useful for flare studies (J. R. Lemen et al. 2012).

In order to compare these AIA 94 Å observations to simulation results, synthetic observables are desired. The solar corona is optically thin to almost all forms of radiation, easing the creation of these synthetic observables (R. Morton 2024). First, the AIA response function for the 94 Å channel is taken from Solar SoftWare (S. L. Freeland & B. N. Handy 1998), calculated using CHIANTIv10 (K. P. Dere et al. 1997; G. Del Zanna et al. 2021), henceforth denoted as $\mathcal{R}$. The number density, n , and the temperature, T , are then taken directly from a snapshot of the MHD simulation. This allows for the calculation of the emissivity of each voxel as

$$\varepsilon(x, y, z) = n(x, y, z)^2 \cdot \mathcal{R}(T(x, y, z)). \quad (9)$$

The optically thin nature of the solar corona then allows for simple integration of this emissivity along the line of sight to produce synthetic emission maps.

3. Simulations

In this work, two simulations are produced for the Active Region AR11283 on 2011 September 6, which produced an X2.1-class flare, one utilizing a NLFF extrapolation following S. Inoue et al. (2014) and described in Section 2.1 and a second employing a non-force-free extrapolation, following the approach developed by Q. Hu & B. Dasgupta (2008), Q. Hu et al. (2008, 2010), and G. A. Gary (2009) and described in Section 2.2. These extrapolations have a grid size of $512 \times 256 \times 256$, corresponding to a volume of $256 \times 128 \times 128$ Mm. The initial photospheric magnetogram from HMI (J. Schou et al. 2012) is shown in Figure 1.

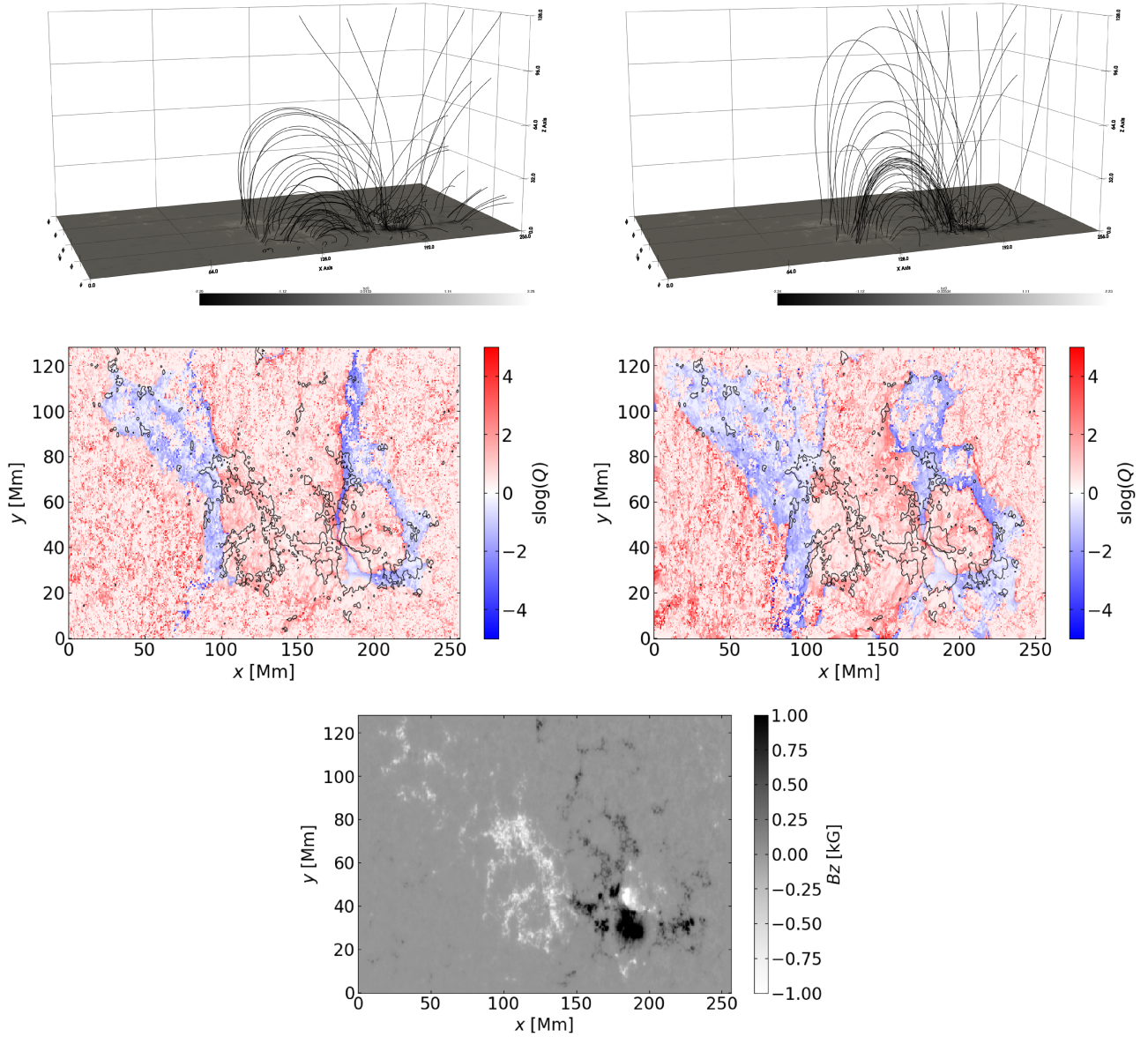


Figure 1. In the left column, the NLFF extrapolation is shown, and in the right, the non-force-free one. The magnetic field lines shown are seeded at the same locations in both, with the field line density proportional to magnetic field strength at the lower boundary. The lower surface in the top row is colored according to B_z at the lower boundary. The second row shows the value of $\log(Q)$ calculated at the lower boundary for the NLFF and non-force-free field extrapolations. Blue corresponds to open field lines and red to closed lines. The black contour shows an absolute value of vertical magnetic field of 0.2 kG. The lower panel shows the vertical magnetic field at the lower boundary, the initial surface magnetogram of AR11283, taken on 2011 September 6 at 20:48 UTC from SDO/HMI. This has been saturated at ± 1 kG for ease of comparison.

Each simulation is performed using the Lare3d code (T. D. Arber et al. 2001) with the same grid as the extrapolations. The initial velocity is set as zero. The velocities at the lower boundary are held as zero throughout each simulation. The normalization constants for length and magnetic flux density are $L_0 = 1.0$ Mm and $B_0 = 0.1$ T, respectively. The normalization constant for density, ρ_0 , is initially held as a free parameter, which has no bearing on the results of the simulation as all internal calculations are performed in normalized units. The value of ρ_0 only affects the interpretation of results when converting into physical units after the simulation has been run. For further discussion on the selection of the value of ρ_0 , see Section 4. A snapshot is taken for each nominal Alfvén time.

The Lare3d code simulates the plasma evolution according to the resistive MHD equations, presented here in normalized,

Lagrangian forms:

$$\frac{D\rho}{Dt} = -\rho(\nabla \cdot \mathbf{v}), \quad (10)$$

$$\frac{D\mathbf{v}}{Dt} = \frac{1}{\rho}(\nabla \times \mathbf{B}) \times \mathbf{B} - \frac{1}{\rho} \nabla P - g\hat{z}, \quad (11)$$

$$\frac{D\mathbf{B}}{Dt} = (\mathbf{B} \cdot \nabla)\mathbf{v} - \mathbf{B}(\nabla \cdot \mathbf{v}) - \nabla \times (\eta \nabla \times \mathbf{B}), \quad (12)$$

$$\frac{D\epsilon}{Dt} = -\frac{P}{\rho} \nabla \cdot \mathbf{v} + \frac{\eta}{\rho} J^2, \quad (13)$$

where P is the gas pressure, g is acceleration due to gravity, $\hat{z}$ is the unit vector in the z -direction, and ϵ is the specific internal energy density.

A plane-parallel stratified atmosphere model is implemented at the beginning of each simulation. The density and pressure are stratified according to

$$\rho = \rho_a e^{-\frac{z}{\Lambda}}, \quad P = P_a e^{-\frac{z}{\Lambda}}, \quad (14)$$

where ρ_a is a constant, set at 2.5; P_a is a constant, set at 1/60; and Λ is the scale height, set as 27.8 (27.8 Mm).

The specific internal energy density is then set at a constant value given by

$$\epsilon = \frac{P}{\rho(\gamma - 1)}, \quad (15)$$

where γ is the ratio of specific heats, set as 5/3. This corresponds to an isothermal atmosphere as specific internal energy density is directly proportional to temperature. Initially, this results in a value of $\epsilon = 1/100$ in normalized units. The value of ρ_0 chosen for production of the synthetic images corresponds to an initial temperature of ≈ 0.55 MK.

The gravity is set to act in the negative z -direction and is set to balance out the pressure gradient term in the momentum Equation (10) such that

$$g = -\frac{1}{\rho} \nabla P = -\frac{1}{\rho_a} \frac{-1}{\Lambda} P_a \approx 2.39 \times 10^{-4}. \quad (16)$$

The resistivity, η , which depends on the local plasma conditions, is defined as follows:

$$\begin{aligned} \eta &= \eta_0 + \eta_1, \\ \eta_0 &= 10^{-5}, \\ \eta_1 &= \begin{cases} 0, & \text{if } j < \alpha \frac{\rho}{\sqrt{\epsilon}} \text{ OR } z < 4 \\ 10^{-3}, & \text{if } j \geq \alpha \frac{\rho}{\sqrt{\epsilon}} \text{ AND } z \geq 4 \end{cases}, \end{aligned} \quad (17)$$

where α is a constant set as 0.002, ρ is the local density, and ϵ is the local specific internal energy density. This mimics the anomalous resistivity triggered by the ion-cyclotron instability (e.g., M. Bárta et al. 2011; M. Gordovskyy et al. 2014).

The initial extrapolations for the NLFF and non-force-free models are shown in the left and right panels of Figure 1, respectively. In the first row, magnetic field lines seeded at the same locations for both extrapolations are plotted. In the second row, the signed logarithm of the squashing factor, Q , is shown at the lower boundary. The squashing factor is a measure of the deformation of the magnetic field line, which passes through a particular point, formalized by V. S. Titov et al. (2002). These squashing factor values have been calculated using the Universal Fieldline Tracer (V. Aslanyan et al. 2024) code. A positive value of squashing factor (shown in red) corresponds to a closed magnetic field line and a negative value (shown in blue) to an open magnetic field line. This allows for the identification of different structures in the initial extrapolations: for example, both produce similar separatrix structures centered around $[x, y] = [200, 50]$ Mm, characterized by a circle of red (closed field lines) surrounded by a ring of blue (open field lines). While Q has a value everywhere, it is important to note that it is a purely geometric measure. A high Q value does not necessarily imply a high field strength and vice versa. To ease the interpretation of the Q maps, the magnetic field strength at the lower boundary is shown in the bottom panel of Figure 1.

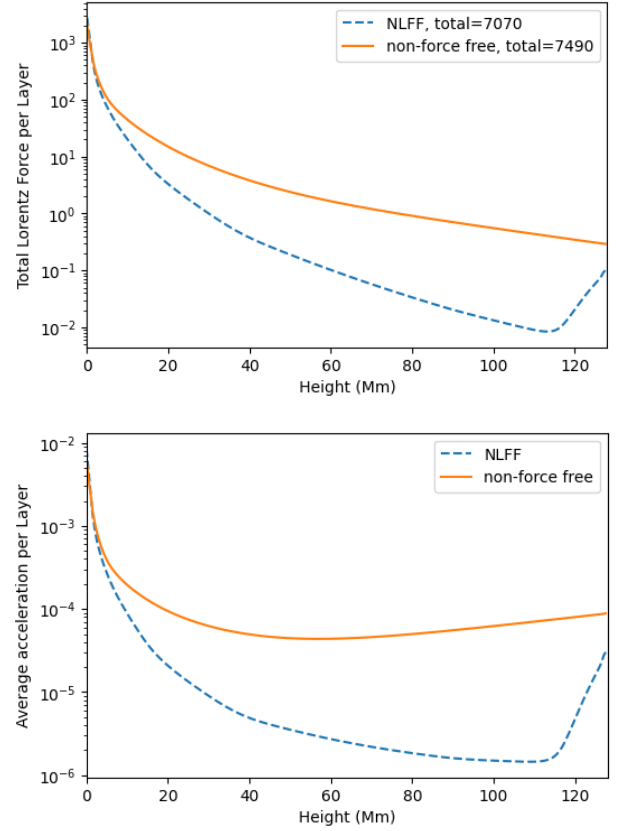


Figure 2. In the first panel, the Lorentz force summed in each layer of the extrapolations is shown on a log-scale as a function of height. The solid line represents the NLFF model, and the dashed line represents the non-force-free model. In the second panel, this is recast as average acceleration per layer using force and density. Both dependent variables are presented in normalized units.

The Lorentz force summed across each layer is shown as a function of height for the NLFF and non-force-free field extrapolations in the top panel of Figure 2. This is presented in normalized units calculated from L_0 , ρ_0 , B_0 following T. D. Arber et al. (2001). These are shown on a log-scale. As expected, the NLFF contains less Lorentz force than the non-force-free extrapolation, and both decay with height. The NLFF extrapolation, despite the name, is not completely force-free. This is due to the fact that the force is not numerically set to zero during the extrapolation. The magnetic field is reached through a magnetic relaxation process followed as described in Section 2.1. Another factor is the lower boundary condition requiring a match with the photospheric magnetogram, which itself is not force-free. In the bottom panel, this force is recast as average acceleration per layer using the stratified density profile shown in Equation (14). Neither simulation contains significant initial acceleration due to the initial magnetic field configuration, meaning that these configurations are stable enough for the study of flares.

We note that the same plane-parallel stratified atmosphere is adopted for both simulations in order to isolate the impact of the magnetic field configuration on the subsequent evolution. While this choice would be consistent with an entirely force-free field extrapolation, it does not enforce full magnetohydrostatic balance for a non-force-free field. In practice, both extrapolations retain residual Lorentz forces due to the non-force-free nature of the photospheric boundary and the

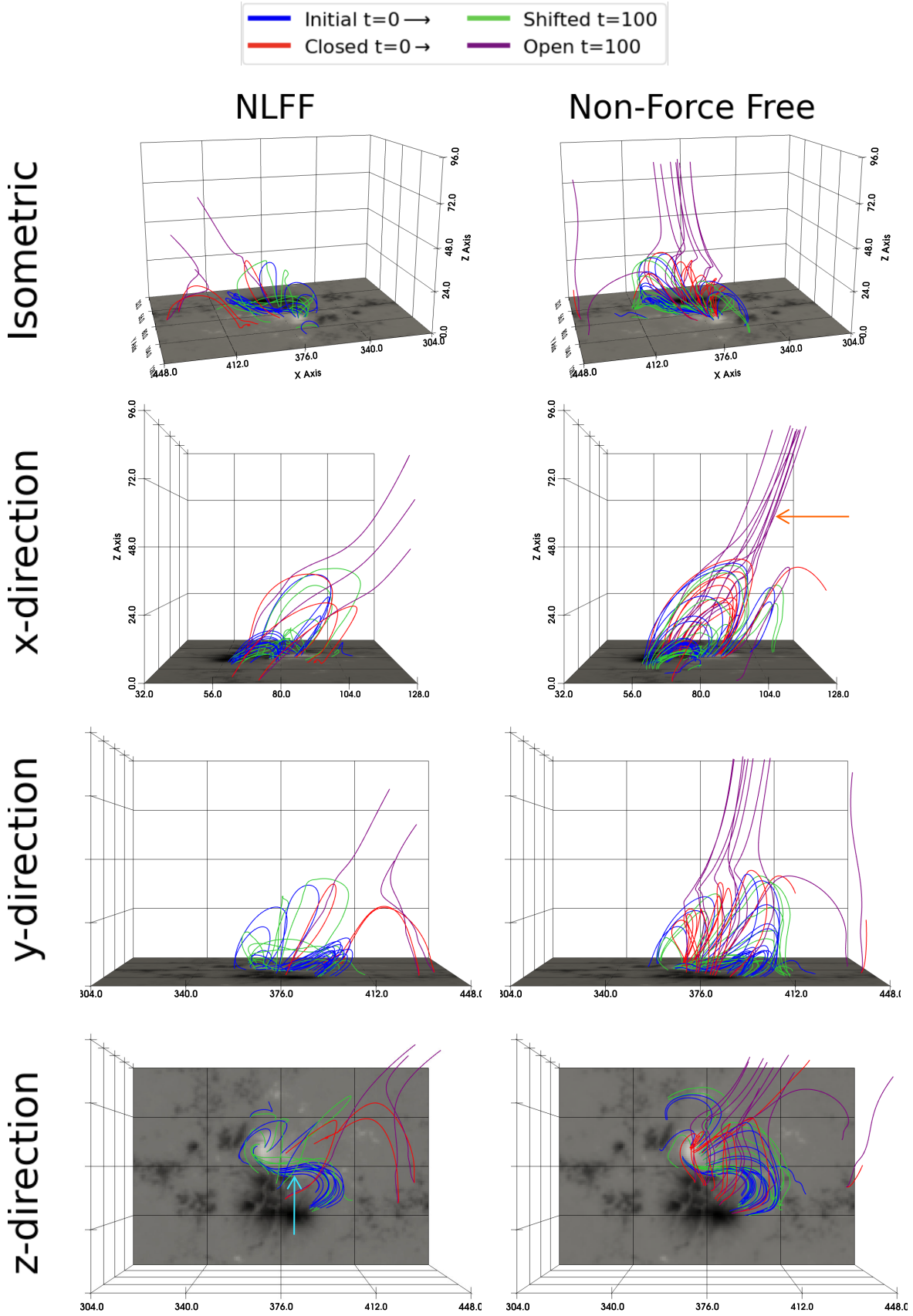


Figure 3. Magnetic field restructuring in the two simulations. The left column shows the NLFF case, and the right column shows the non-force-free case. All panels correspond to the same times, with field line connectivity compared between $t = 0$ and $t = 100t_A$. The rows show different viewing angles: isometric and projections along the x -, y -, and z -axes. Red field lines indicate structures that are initially closed at $t = 0$, while the corresponding purple lines show their connectivity at $t = 100t_A$, highlighting field lines that become open. Blue field lines denote structures at $t = 0$ whose footpoints undergo significant displacement (>5 Mm), with their later positions shown in green at $t = 100t_A$.

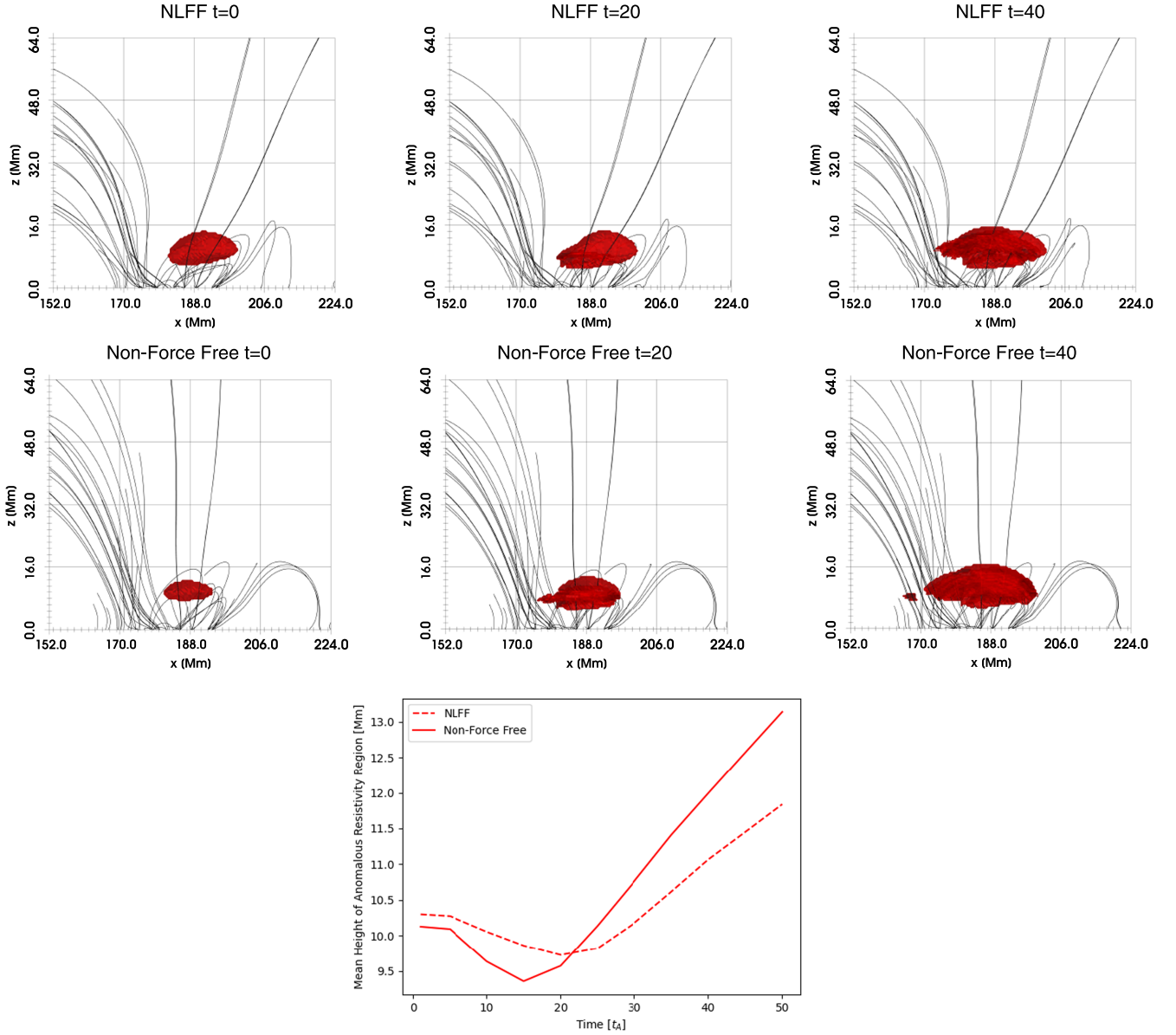


Figure 4. In the top row, results of the simulation initialized with the NLFF extrapolation are shown, and in the middle row, the non-force-free one. The left column shows the initial configuration, while the next two columns show the simulation at $t = 20, 40 t_A$. The magnetic field lines shown are seeded at the same locations in both, with the field line density proportional to magnetic field strength at the lower boundary. The red volume corresponds to the location where anomalous resistivity is active during that stage of the simulation. The bottom panel shows the mean height of the anomalous resistivity region in both simulations over time, with the NLFF and non-force-free models being represented by the dashed and solid lines, respectively.

numerical construction methods. The non-force-free model can therefore be interpreted as representing a stressed preeruptive state. Constructing a fully consistent magnetohydrostatic equilibrium for such fields is beyond the scope of the present study.

We stress that the non-force-free field should not be interpreted as a corona containing large Lorentz force imbalances throughout the entire volume. The top panel of Figure 2 demonstrates that the Lorentz force is concentrated primarily near the lower boundary and decreases rapidly with height. This behavior is expected because the photosphere and lower solar atmosphere are known to be non-force-free, whereas the higher corona is generally closer to a force-free state (G. A. Gary 2001). Similar concentrations of Lorentz force near the lower boundary are commonly found in non-force-free extrapolations used to initialize simulations (e.g.,

A. Prasad et al. 2018, 2020, 2023; S. S. Nayak et al. 2019; C. Liu et al. 2020; S. Kumar et al. 2022; M. V. Siewra et al. 2026).

It is also important to note that the preflare atmosphere is not expected to be perfectly force-free. Continuous stressing by photospheric motions, for example, can drive the magnetic field away from a force-free equilibrium as free magnetic energy accumulates prior to eruption (H. Wang et al. 2002; R. Wang et al. 2018). In this context, the NLFF and non-force-free extrapolations may be viewed as representing different stages in the evolution of an active region rather than mutually exclusive physical states. The NLFF field represents a configuration closer to equilibrium, whereas the non-force-free field corresponds to a more strongly stressed preeruptive state containing additional free magnetic energy available for release during the flare.

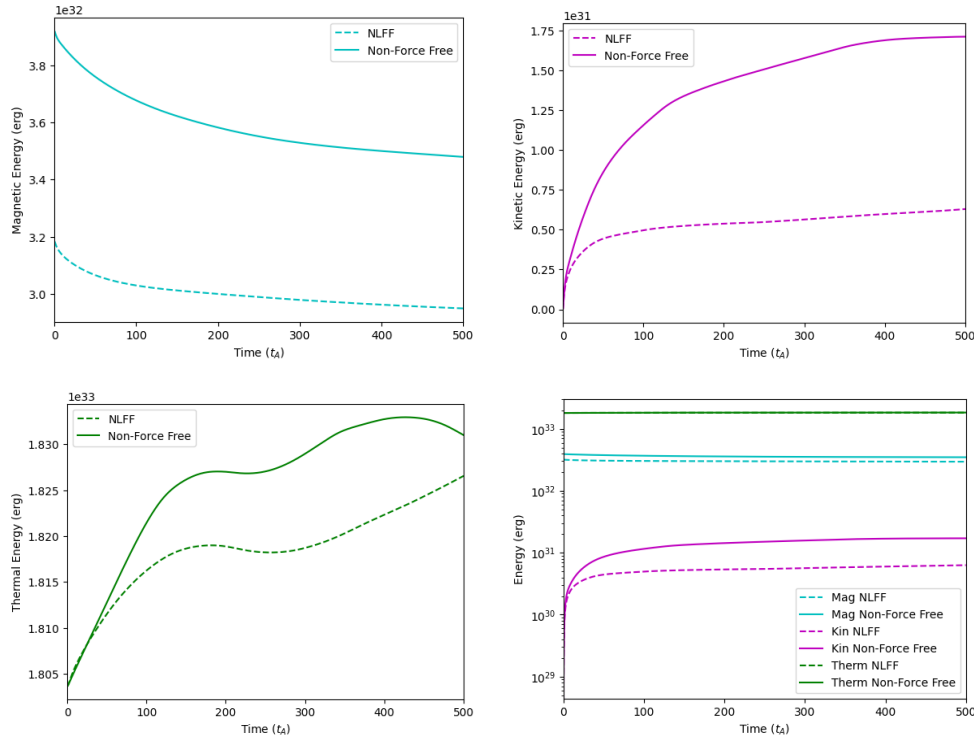


Figure 5. Energy over time for both the NLFF (dashed lines) and non-force-free (solid lines) simulations. The first plot (cyan) shows magnetic energy, the second (purple) shows kinetic energy, the third (green) shows thermal energy, and the fourth shows all of them together with a log-scale for comparison.

Although the non-force-free extrapolation does not satisfy a strict magnetohydrostatic equilibrium, the associated accelerations remain small throughout the domain, as shown in the bottom panel of Figure 2. This indicates that the configuration is sufficiently close to equilibrium to permit meaningful evolution on flare timescales.

4. Results and Analysis

Each of these simulations is then allowed to run for 500 nominal Alfvén times. The magnetic field restructuring in each of these two simulations is shown in Figure 3. The left and right columns show the NLFF and non-force-free cases, respectively. The top row shows an isometric view, and the next three rows show views from the x -, y -, and z -directions. The red lines show field lines that are initially closed at $t = 0$, which become open at $t = 100t_A$ and are shown in purple. The blue lines show field lines at $t = 0$ whose end points move by more than 5 Mm across the solar surface to the green field lines shown at $t = 100t_A$.

Initially field lines are seeded at the same locations in both of the simulations. However, many more field lines are shown in the non-force-free case as only those field lines that have significantly changed connectivity are plotted. This indicates a larger shift/restructuring of the magnetic field in the non-force-free simulation. Further, there are a larger number of red $\rightarrow$ purple (closed $\rightarrow$ open) field lines in the non-force-free case. This magnetic field restructuring shows a twisted sigmoid-shaped magnetic flux tube (blue $\rightarrow$ green as the flux rope untwists), which is denoted by the cyan arrow in Figure 3. This sigmoid structure is seen at the same location in both simulations. Also shown are an overlying set of red field lines that open into the upward purple field lines by the end of the event, indicated by the orange arrow in Figure 3.

The initial volume in which the anomalous resistivity is active, and its evolution is shown for the NLFF and non-force-free simulations in the top and middle rows of Figure 4, respectively. This shows the progression through $t = 0, 20, 40 t_A$ and the anomalous resistivity volume can be seen to increase in height and volume throughout time in both simulations. The average height of this anomalous resistivity volume is tracked in the bottom panel for both simulations as a function of time. This starts higher in the NLFF model and rises, but more slowly than in the non-force-free model. It should be noted that a region with active anomalous resistivity is not all that is required for reconnection to occur. A sufficiently high value of J^2 is also required. The non-force-free model shows greater magnetic field line restructuring due to its higher values of J^2 , despite the size and shape of the anomalous resistivity region being roughly similar in both simulations.

The evolution of different types of energy within the flare simulations are shown in Figure 5, with the NLFF shown by the dashed lines and the non-force-free by the solid. The NLFF magnetic field initially contains 3.18×10^{32} erg of magnetic energy, losing 2.3×10^{31} erg, and the non-force-free field initially contains 3.92×10^{32} erg and loses 4.4×10^{31} erg. These are comparable to the expected energy releases due to an X-class flare (C. S. Moore et al. 2014). The NLFF field also starts with less magnetic energy, as would be expected of a force-free field. The energy imparted in the form of thermal energy is of a similar order of magnitude, with an increase of 2.3×10^{31} erg in the NLFF case and 2.7×10^{31} erg in the non-force-free case. This suggests that non-force-free initializations may help to alleviate the difficulty that NLFF-initialized models have providing as much magnetic energy as is needed to produce the amount observed to be released in flares, which

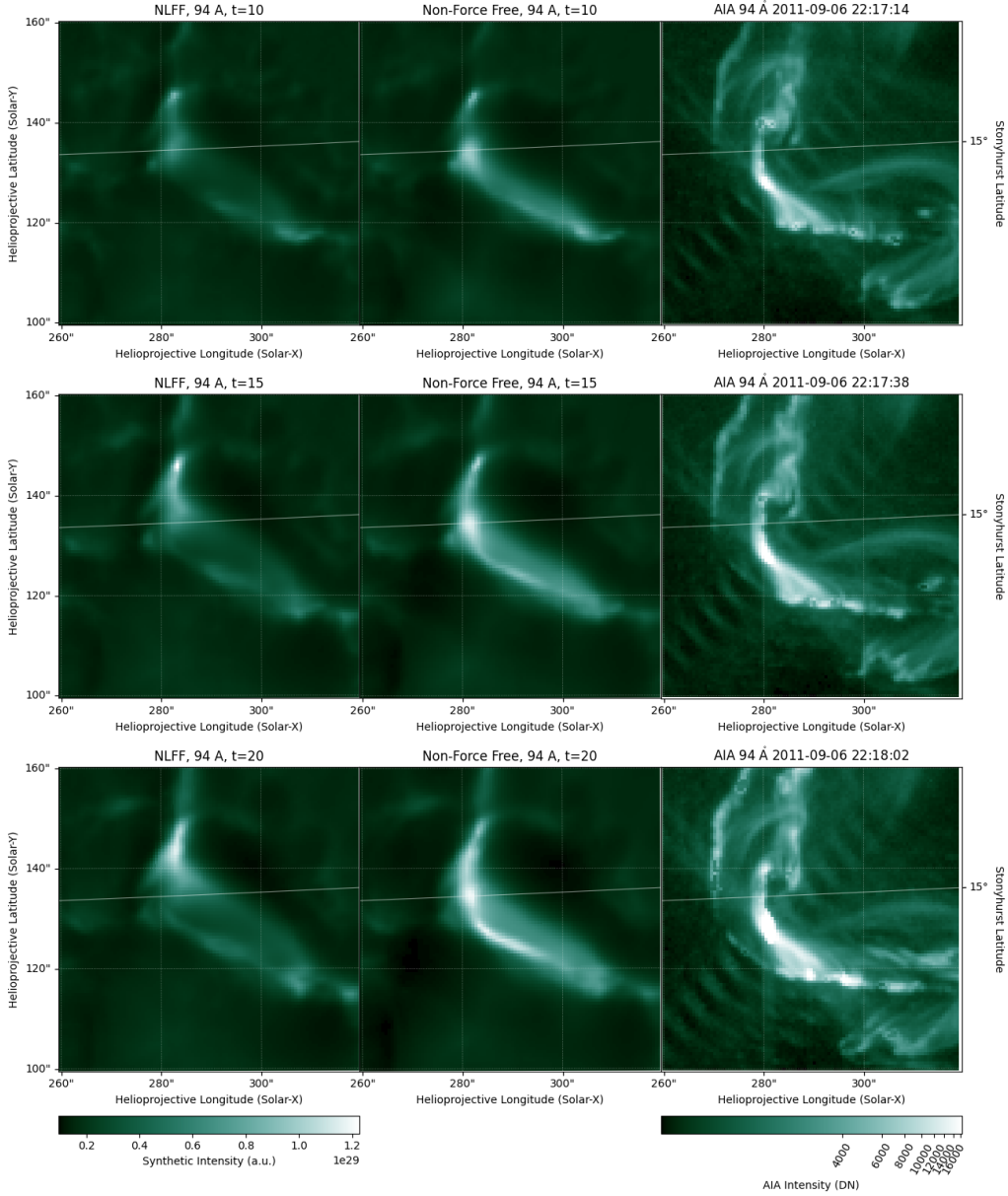


Figure 6. A comparison of the synthetic and measured 94 Å emission. In the left and central columns, synthetic emission is shown from the NLFF and non-force-free initialized simulations, respectively. The top row shows the simulations at $t = 10t_A$, the middle row at $t = 15t_A$, and the bottom row at $t = 20t_A$. The synthetic emission is scaled to the brightest emission of the six panels (at $t = 20t_A$ in the non-force-free simulation), indicated by the lower-left color bar. The right column shows the measured AIA 94 Å emission, with the top, middle, and bottom panels taken at 22:17:14, 22:17:38, and 22:18:02 UT, respectively. Each measured intensity image is scaled to the brightest intensity in the latest unsaturated image, indicated by the color bar in the lower right. An animation of this figure is available in the online version of the article. The animation contains three sections: (1) the synthetic emission from the NLFF simulation from $t = 0$ to $100t_A$; (2) the synthetic emission from the non-force-free simulation from $t = 0$ to $100t_A$; (3) the measured AIA 94 Å emission from 22:14:01 to 22:20:02 UT.

(An animation of this figure is available in the [online article](#).)

has been noted by previous works (e.g., M. Gordovskyy et al. 2020). Note that the energies are not exactly balanced due to the “open” boundary condition at the top of the domain.

Synthetic AIA 94 Å emission maps produced at $t = 10, 15, 20t_A$ are shown in the left and central columns of Figure 6. These are calculated according to Section 2.3. The left column shows the NLFF simulation, and the central column shows the non-force-free case. In the right column, the intensity measured by AIA is shown at with the same projection utilizing SunPy (T. S. Community et al. 2020). The final of these images is taken at 22:18:02 UT. This time step is chosen as it is the final AIA image before the detector is

saturated by the flare, although an animation of the AIA 94 Å images is available in the online version of this article. Both simulations recreate the location of greatest emission in a similarly shaped curved bright feature. However, the brightness in the NLFF simulation is concentrated in the top left of the structure. This is not seen in the non-force-free case, where the entire structure is bright, similar to the observed case shown in the lower panel. Note that we do not expect the flare ribbons visible in the AIA observations to be visible within the simulations due to the lack of a realistic chromosphere.

An animation of the synthetic emission shown in the left and central columns of Figure 6 is available in the online version of

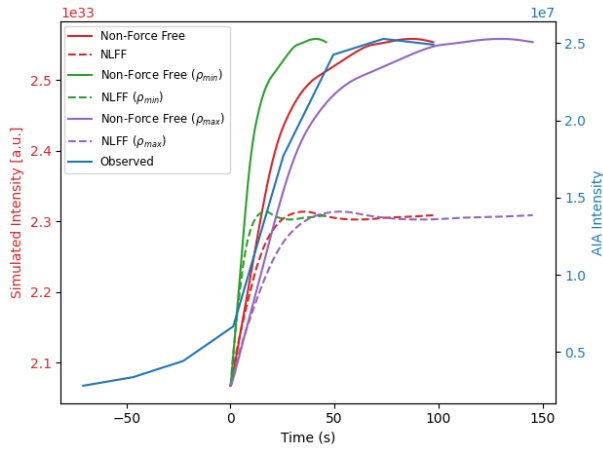


Figure 7. The green, red, and purple lines show the synthetic 94 Å light curves for both of the simulations, with density scaling factors corresponding to density at the upper domain boundary of $\rho_t = 2 \times 10^8$, 9×10^8 , and 10^{10} cm^{-3} , respectively. The solid lines corresponds to the non-force-free case, and the dashed lines to the NLFF case. The blue line shows the measured AIA 94 Å light curve.

this article. The previously mentioned differences in structure between the two simulations are visible. Further, an eruption is visible in both simulations moving toward the top right of the field of view. This eruption is also visible in the observed AIA emission. The authors suggest that this is hot material traveling along the newly open purple field lines shown in Figure 3 by the orange arrow.

When examining the timescale of these flare simulations, it is important to note the units being considered. The Lare3d code is normalized according to three quantities and their associated normalization constants: length (L_0), density (ρ_0), and magnetic field strength (B_0). Two of these parameters are set in relation to the original surface magnetogram ($L_0 = 1.0 \text{ Mm}$, $B_0 = 0.1 \text{ T}$). However, ρ_0 is not fixed as the density profile of the stratified atmosphere is not measured. The normalization constant for time is the nominal Alfvén time, calculated in terms of the declared constants as

$$t_0 = t_A = \frac{L_0 \sqrt{\rho_0 \mu_0}}{B_0}, \quad (18)$$

where μ_0 is the magnetic permeability of free space. By considering a range of physically reasonable particle densities at the top of our 128 Mm tall computational domain $\rho_t = [2 \times 10^8, 10^{10}] \text{ cm}^{-3}$, we arrive at a range of values for $t_0 = [0.09, 0.29] \text{ s}$. This range of density scalings is considered in order to best match the speed of the simulated flare to the observed flare. As this is simply a change of scaling parameters, this has no effect on the physical evolution of the simulation, only the conversion of simulation units to physical units.

Synthetic 94 Å light curves for each of the simulations are shown in Figure 7 with the solid line corresponding to the non-force-free case and the dashed line to the NLFF simulation. A selection of three time scalings are shown, with the minimum and maximum values of density at the upper boundary ($\rho_t = 2 \times 10^8, 10^{10} \text{ cm}^{-3}$) shown in green and purple, respectively. Also shown for comparison is the 94 Å light curve measured by AIA. Finally, a “tuned” density scaling parameter is selected to match the timescale of the observed

AIA light curve, shown in red and corresponding to a value of $\rho_t = 9 \times 10^8 \text{ cm}^{-3}$. Although both simulations show a similar temporal evolution, the non-force-free case is brighter, as expected due to the larger energy release in this simulation. This discrepancy in brightness is similarly visible in Figure 6.

5. Conclusions

In this work, we have performed a controlled comparison of data-driven MHD flare simulations initialized with either a conventional NLFF magnetic field extrapolation or a non-force-free magnetic field model that self-consistently incorporates plasma forces. Although the two extrapolation techniques produce broadly similar large-scale magnetic structures prior to flare onset, we find that their subsequent magnetic reconnection, energy release, and flaring evolution differ substantially. In particular, the non-force-free model undergoes more extensive magnetic restructuring and releases significantly more magnetic energy during the flare, alleviating the long-standing difficulty of NLFF-initialized simulations underestimating the energy budget of observed X-class flares.

These differences in magnetic evolution have clear observational consequences. Synthetic EUV emission calculated for the AIA 94 Å channel reveals marked contrasts between the two simulations, with the non-force-free model producing a 1 brightness distribution and flaring loop structure that more closely resemble the observed flare emission. In contrast, the NLFF-initialized simulation exhibits a more localized and less realistic emission pattern. This demonstrates that assumptions made in constructing the initial coronal magnetic field can propagate directly into observable flare signatures.

Finally, our results highlight the diagnostic power of synthetic EUV emission in assessing the realism of data-driven flare simulations. Direct comparison between simulated and observed emission provides a stringent and physically meaningful test of competing magnetic field models. Taken together, these findings suggest that non-force-free extrapolations offer a promising pathway toward more realistic flare simulations and motivate their broader adoption in future data-constrained MHD studies of solar eruptive events.

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Facilities: SDO (W. D. Pesnell et al. 2012).

Data Access Statement

Due to the data volume (approaching 3 TB), the MHD simulation data are available, in various stages of reduction format, directly from the first author (William Bate; w.bate@herts.ac.uk).

ORCID iDs

W. Bate  <https://orcid.org/0000-0001-9629-5250>
M. Gordovskyy  <https://orcid.org/0000-0003-2291-4922>
A. Prasad  <https://orcid.org/0000-0003-0819-464X>
A. S. Brun  <https://orcid.org/0000-0002-1729-8267>
A. Strugarek  <https://orcid.org/0000-0002-9630-6463>
M. V. Sieyra  <https://orcid.org/0000-0002-1536-8508>
P. K. Browning  <https://orcid.org/0000-0002-7089-5562>
S. Inoue  <https://orcid.org/0000-0001-5121-5122>
K. Matsumoto  <https://orcid.org/0000-0003-2002-0247>
A. Roddanavar  <https://orcid.org/0000-0003-1363-3096>

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