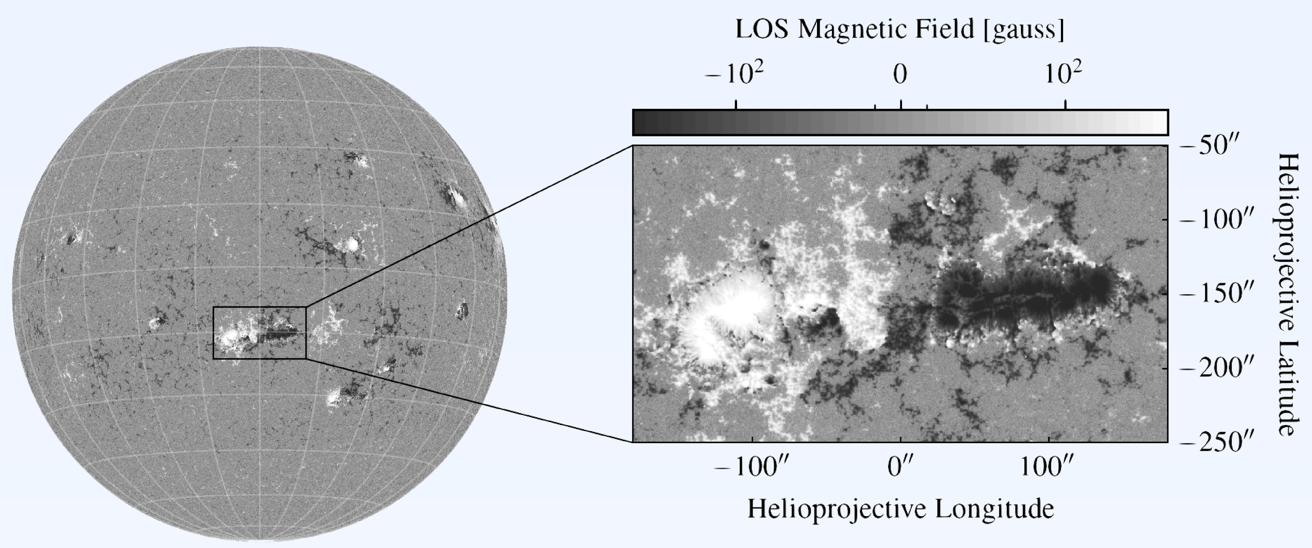
Three-Dimensional Solar Magnetic Field Extrapolation Using Analytical Magnetohydrostatic Equilibrium Solutions

Lilli Nadol, University of St Andrews, UK, lmn6@st-andrews.ac.uk

Thomas Neukirch, University of St Andrews, UK



Background

Free energy stored in the coronal magnetic field drives solar events like flares and CMEs, necessitating accurate modelling for analysis and prediction. Without direct coronal measurements, extrapolation methods rely on photospheric observations as boundary conditions.

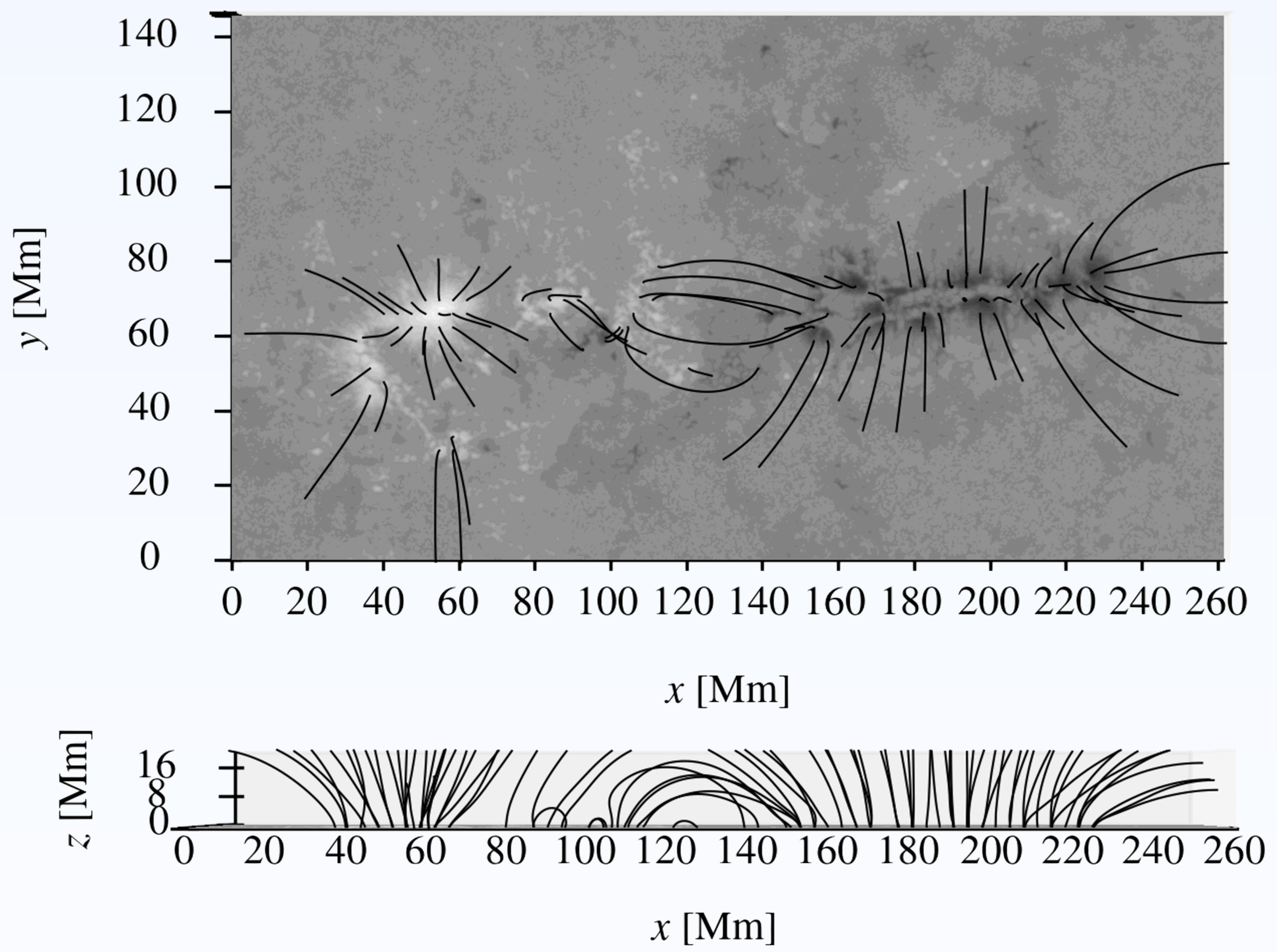
Potential and linear force-free methods, while simple to apply, have limitations: potential fields lack free energy to model active regions, and the force-free assumption fails in the lower atmospheric layers, creating observation-model inconsistencies.

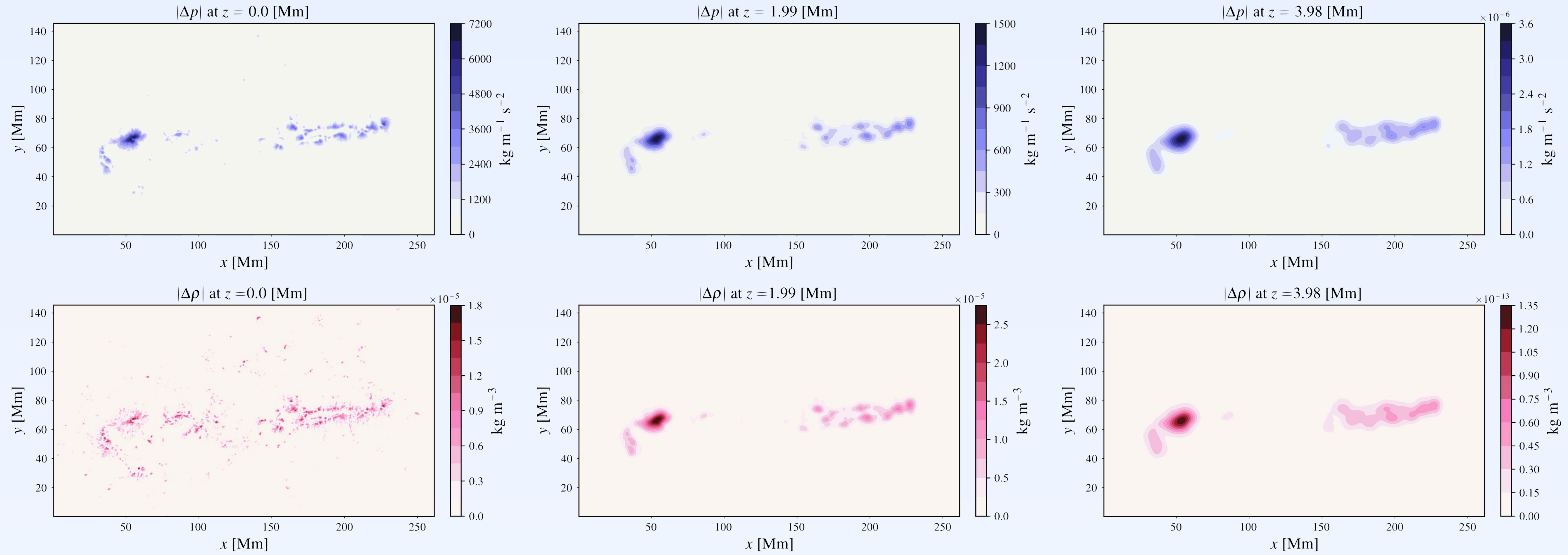
Magnetohydrostatic (MHS) approaches offer an alternative that accommodates for the non-force-free conditions in the photosphere and chromosphere.

Model

Our model solves the MHS equations including a transition from non-force-free to force-free conditions through a special formulation of the current density.

Compared to previous work by Low (1992) and Neukirch & Wiegelmann (2019), our implementation provides a more flexible mathematical description and an expanded parameter space in combination with increased numerical performance. We used an asymptotic solution for computational efficiency and developed a Python code for practical application of the model.





Example

We present a demonstration of the model using SDO/HMI data (see boundary condition on far left). The centre figure shows magnetic field lines in the x-y and x-z planes; The figure above shows pressure and density variations at different heights above the photosphere. In the model, pressure and density consist of a 1D background atmosphere plus a 3D variation term that can take negative values.

A thorough evaluation of our model against other methods can be found in Nadol & Neukirch (2025).

Conclusions

Our model advances MHS extrapolation with optimised computational performance through using an asymptotic solution as well as through utilising Python's scientific libraries and efficient handling of multi-dimensional arrays. It enables routine magnetic field extrapolation from observations by instruments such as SDO/HMI and Solar Orbiter/PHI. The model contributes to solar physics research, particularly where capturing the transition from non-force-free to force-free conditions is essential.

Code

Our MHS extrapolation algorithm is implemented in Python, with a preliminary version and documentation available at https://github.com/LMNadol/MHSXtraPy.

References

Neukirch, T., & Wiegelmann, T. (2019). Solar Physics, 294(12), 171.

Low, B. C. (1992). The Astrophysical Journal, 399, 300.

Nadol, L., & Neukirch, T. (2025). Solar Physics, *preprint*.

Abstract

MHSExtraPy

EGU General Assembly

University of St Andrews

International Space Science Institute