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Coronal Magnetic Field Modelling

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The coronal magnetic field produces solar activity including solar flares and coronal mass ejections, which drive space weather events at the Earth. Hence there is a strong motivation to be able to accurately model the state and evolution of the coronal magnetic field.

Methods for modelling the coronal field have developed substantially in recent decades, from the application of static field models (e.g. the force-free model[1]) to dynamic models such as the magneto-frictional model and variants of magneto-hydrodynamics (MHD). Historically the use of MHD in solar modelling has been restricted to simulations with artificial boundary conditions ("data-inspired" models), but it is increasingly being applied using real solar data. The models differ in the physics being included, and in how, and the extent to which, they incorporate solar data at the numerical boundaries. Methods which use boundary data at an instant in time are often referred to as "data-constrained" models, and methods which use time-dependent boundary data are called "data-driven" models[1].

These approaches have been successful in reproducing observed features and behaviours of coronal magnetic fields, for example the shape of observed flare emission based on field topology[2], the appearance of twisted magnetic flux ropes[3], the rise of flux ropes[4], and eruptions[5]. Data constrained models have enabled calculation of global field properties such as magnetic helicity and magnetic energy[6]. A data-inspired radiative MHD model including a convection zone has been shown to produce many of the features of a solar flare, including a realistic synthetic soft X-ray light curve[7].

Despite these qualitative successes, the quantitative validation of coronal magnetic models remains a challenge. This challenge is partly due to the lack of detailed coronal observations to serve as a ground-truth reference.

There is a need for intercomparison of the results of different models, and benchmarking of models against reference simulations[8]. Outstanding questions in modelling include how best to incorporate solar data and accommodate missing boundary data so as to ensure consistency with the physical model[9], the ability of the models to reproduce energy release processes in solar activity which involve sub-grid scale physics, and how to assign uncertainties to model outputs. Some guidance may be provided by numerical weather prediction, which has continuously improved since the 1970s and has well-established approaches (data assimilation and ensemble forecasting) to deal with imperfect observations and models.

In this talk we will review the current state of coronal magnetic field modelling, in particular data-driven modelling, with a focus on the incorporation of solar boundary data and methods of validation of model results. We will also discuss directions for future work, including possible uses for Physics Informed Neural Network (PINN) models[10].

References

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[1] This terminology is at odds with the standard meaning of a "data-driven model" as a computational model which uses data rather than a physical model to establish relationships between inputs and outputs.