Leveraging the efficiency of Physics-Informed Neural Networks (PINNs) to monitor the evolution of solar active regions

Alexis Blaise

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1 Abstract

The Sun exhibits a cyclic, magnetic activity that impacts our technological society on Earth. This activity originates in regions of concentrated magnetic flux called active regions. Active regions can produce impulsive eruptions, known as solar flares, when free magnetic energy that is built-up by surface flows and magnetic field emergence gets released via magnetic reconnection. Understanding the processes leading to this release is key to better anticipating these outbursts, but currently requires computationally expensive extrapolations to probe.
Non-linear force free (NLFF) extrapolation is one such method for reconstructing the topology and evolution of the magnetic field above active regions. Active regions that survive over several months can contribute significantly to the total flaring output of the Sun, and would require hundreds of extrapolations to monitor correctly. Typically, NLFF extrapolations are computationally expensive and so are not well-suited to study the build-up of free magnetic energy in these long-lived active regions.
So we used a physics informed neural network (PINN), called NF2 [1], to efficiently reconstruct the active region magnetic field. The PINN is driven by observations of the surface magnetic field and aims to satisfy the equations of the NLFF extrapolation in a 3D domain, whilst obeying physical laws, like div B = 0. The PINN finds the best weights for the 8 layers of 256 neurons (randomly sampling the 3D domain) that satisfy the surface magnetic field, NLFF equations, and divergence-freeness of the magnetic field. To increase efficiency, the PINN is trained iteratively using the weights from the previous time interval. This allows the PINN to produce extrapolations at a higher speed than standard methods.
It unlocked the possibility to extrapolate from nearly 800 magnetograms (one week), the magnetic structure of the active regions within a day of computation on an A100 GPU. From this we can monitor the build-up of free magnetic energy over periods of weeks to months which helps us in our understanding of the solar flares physics.

PINNs are interesting new techniques that can help accelerate progress in solar physics. We may in a near future be able to reconstruct active region magnetic field efficiently enough to use it as indicators for solar eruptions or as input for solar wind models in open field lines configurations.

[1] : Jarolim, R., Thalmann, J.K., Veronig, A.M. et al. Probing the solar coronal magnetic field with physics-informed neural networks. Nat Astron 7, 1171–1179 (2023)