Machine Learning analysis of self-consistent magnetic flux ropes realized in M-dwarf dynamo simulations

Connor P. Bice[1,2] ; Juri Toomre[1,2]

(1) JILA; (2) Department of Astrophysical & Planetary Sciences, University of Colorado Boulder

Motivation

Despite their small sizes, cool temperatures, and dim luminosities, M-dwarf stars are well known for the vigorous magnetism many of them display. Large flares can occur with extreme frequency on these stars, and in the case of superflares, may briefly outshine the rest of the star by factors as large as 1000. The active regions which give rise to these flares are thought to be formed by the rise of buoyant magnetic flux ropes born from dynamo action deeper in the convective interior of the star.

MHD simulations of such interiors have yielded great insight into the global scale dynamo processes and their interaction with stars' flow structures, but precious few have ever identified self-consistently generated buoyant flux ropes (e.g. *Nelson et al. 2011*). This is in part due to these structures defiance of well-constrained mathematical isolation, necessitating extremely time-consuming "by-hand" approaches.

We introduce here the first automated tool for the identification and tracking of self-consistent magnetic flux ropes in global 3D MHD simulations, allowing for comprehensive analyses of the dynamics of such structures should they be present, without investing dozens of hours.

Simulation

The magnetic field lines considered in training and testing the pipeline were integrated from the fields of case D2ta of *Bice & Toomre 2020*. This global anelastic MHD model of an M2 star was computed in the open-source simulation code *Rayleigh* (*Featherstone & Hindman 2016*) and has the following properties:

- A 1D background state computed in MESA (*Paxton et al. 2010*)
- A stably-stratified radiative interior below its convective envelope, which contains a diffusively mediated tachocline of shear
- Extremely strong, time-steady toroidal magnetic fields in places reaching amplitudes in excess of 50 kG.
- A magnetic event leading to the simultaneous release from the tachocline and rise of more than 10^{37} erg of magnetic energy.

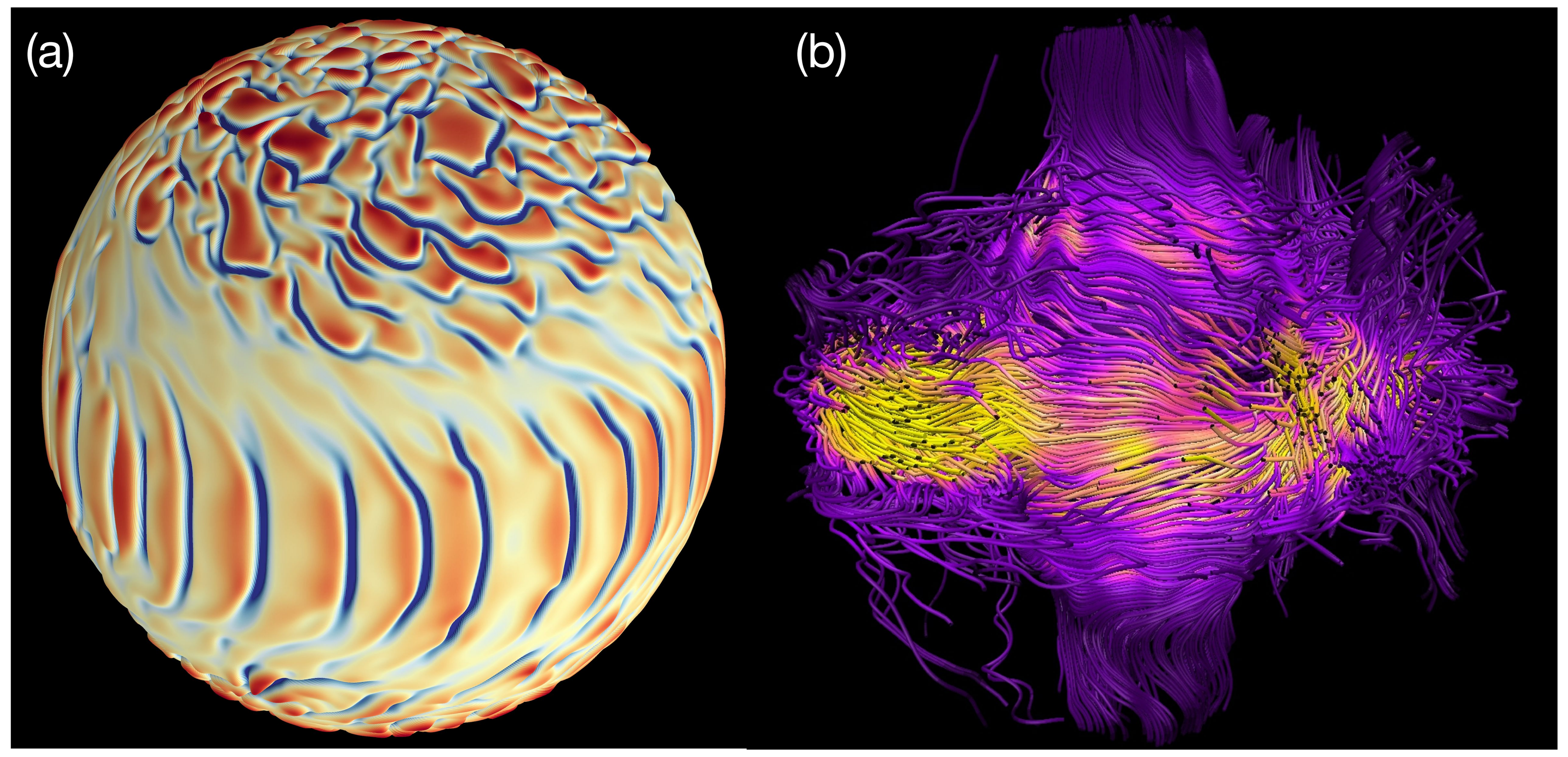


Figure 1. (a) Visualization of the near-surface radial velocity in case D2ta with warm, red upflows and cold, blue downflows. Axially-aligned Busse columns can be seen near the equator, with more isotropic convection visible near the north pole. **(b)** Visualization of the magnetic fields generated in case D2ta, with bright colors indicating stronger fields. A cutaway reveals the interior of the equatorial wreath. The remains of several emerged loops can be seen.

An Automated Pipeline

1. Tens of thousands of magnetic field lines are integrated from randomly seeded locations in snapshots of the stellar interior spanning the desired interval.
   a. Oversaturating the volume with field lines ensures that all structures of interest will appear on at least one field line.
   b. Physical variables which will be used in classification and segmentation are recorded at all points along each field line.
2. A neural network designed for binary classification scores each field line, with higher scores indicating a higher probability that the line contains a rising loop.
3. Field lines meeting a threshold score are fed through a separate neural network designed for segmentation,, potentially identifying sections of the field line as candidate loops and discarding the rest.
4. Redundant loop candidates from different field lines passing nearby through the same structure are grouped together.
5. The approximate evolution of each loop candidate is estimated and used to pair loop candidates to their counterparts in the following snapshot, if present.
6. A set of evolution trees containing all loop candidates across every snapshot is constructed. From it, rising loops are identified and presented for further dynamical analysis.

The Near Future

- Development on this project is expected to be complete within weeks of the start of Cool Stars 20.5.
- Preliminary testing of the neural networks has shown promise in models of both fully convective and solar-like stars without needing to re-train, with more rigorous validation in non-M2 geometries to come.
- A paper detailing the pipeline and analyzing the dynamics of rising loops identified in case D2ta is soon to be submitted
- Following publication, the pipeline will be made freely available to anyone interested in applying it to their own simulations.

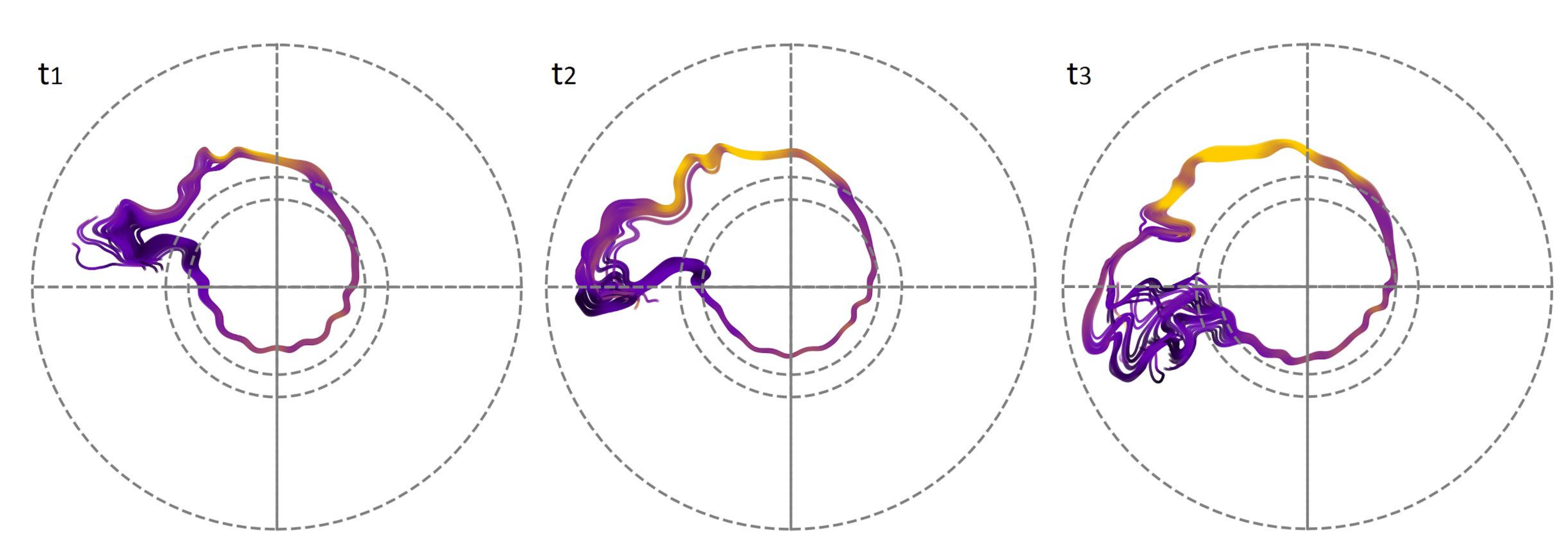
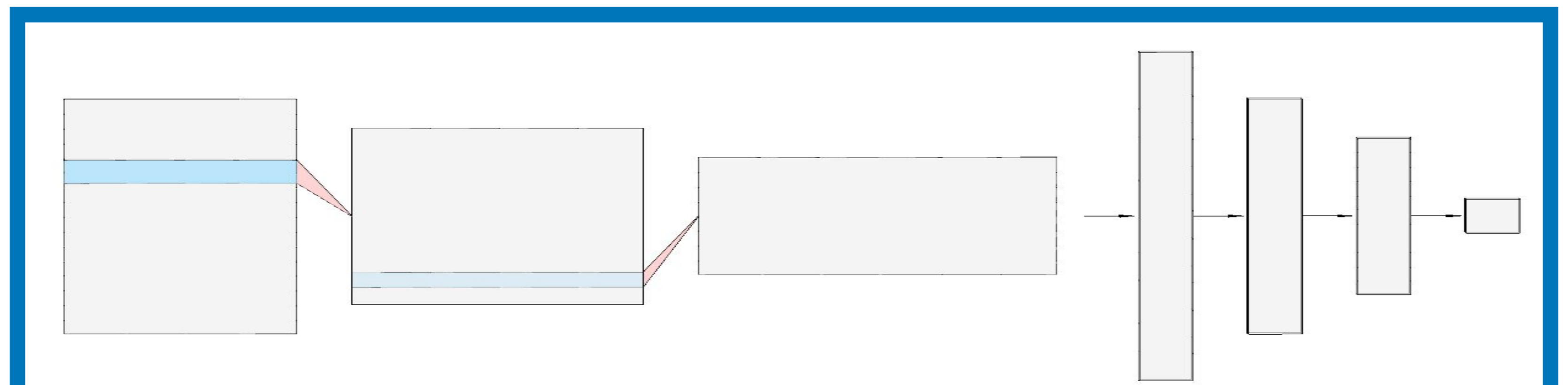


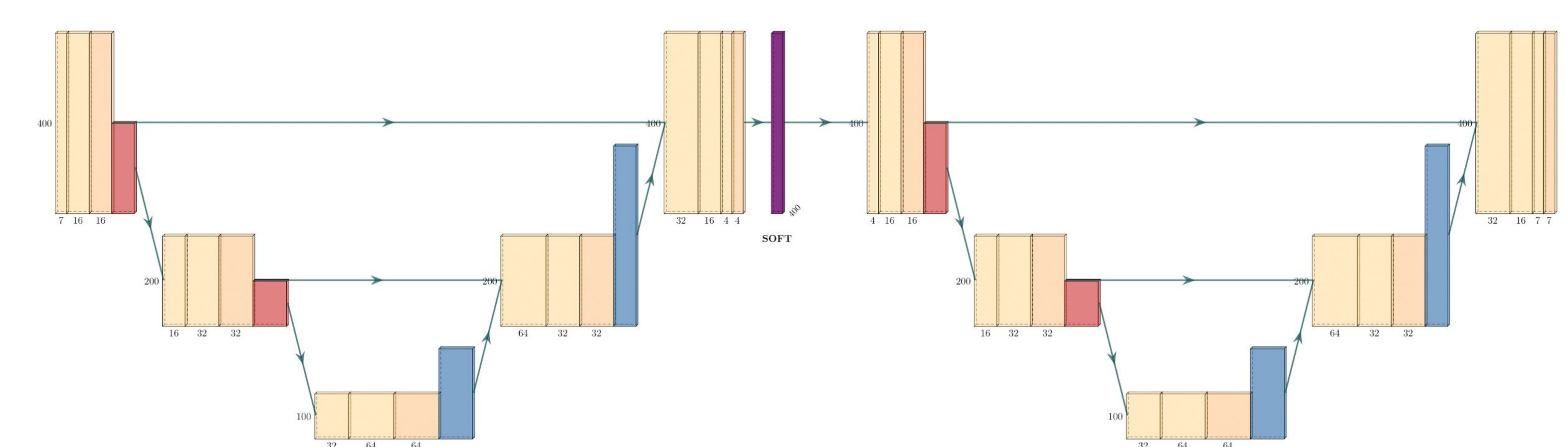
Figure 2. Field line tracings of a sequence of hand-identified loops rising from the tachocline in case D2ta, seen from above the north pole of the model at instants separated by roughly 24 days each.

Classification Network



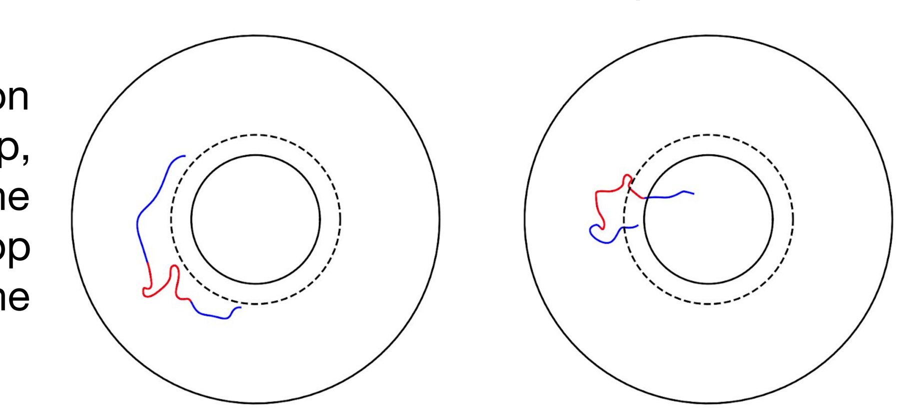
- Inputs are 400 "pixel" long field lines with 11 channels encoding derivatives of the 3 spherical coordinates, line curvature, cylindrical radius and height, radial velocity, radial and horizontal magnetic field strength, entropy, and plasma β.
- Architecture adapted from the popular AlexNet (*Krizhevsky et al. 2017*), featuring 2 convolution layers, each followed by max pooling and linear rectification, and 3 fully connected layers, each followed by linear rectification.
- Trained on 1800 hand-classified field lines Stochastic Gradient Descent using a Cross-Entropy loss
  - 20% dropout in the Conv layers and 50% dropout in the FC layers
  - Selected model achieved a positive detection probability of 0.96 and false positive rate of 0.04

Segmentation Network



- Architecture is an adapted W-Net (e.g. *Xia & Kulis 2017*)
  - The first "U" is an encoder, classifying segments of input. Its output is all that is taken when segmenting out loop candidates
  - The second "U" is a decoder, reconstructing the input image from the classified segments. It is used only during training.
- Trained unsupervised on 180,000 field lines with soft-N-cut loss for the encoder, RMS error loss for the full network, and 20% dropout.

Figure 3. An example segmentation of a field line containing a loop, seen projected into (a) the xy-plane and (b) the xz-plane. The loop candidate is shown in red, while the discarded section is in blue.



Contact: connor.bice@colorado.edu

The calculations presented here were performed on the NASA Pleiades supercomputer, and were supported by NASA grants NNX17AG22G and 80NSSC20K1543

References:

- *Bice, C.P. & Toomre, J. 2020, ApJ, 893, 107.*
- *Featherstone, N.A. & Hindman, B.W. 2016, ApJ, 818, 32.*
- *Krizhevsky, A., Sutskever, I., & Hinton, G.E. 2017. CACM, 60, 84.*
- *Paxton, B., Bildsten, L., Dotter, A., Herwig, F., Lesaffre, P., et al. 2010, ApJS, 192, 3.*
- *Nelson, N.J., Brown, B.P., Brun, A.S., Miesch, M.S., & Toomre, J. 2011, ApJL, 739, L38.*
- *Xia, X. & Kulis, B. 2017. arxiv:1711.08506.*