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Predicting coronal eruptions from photospheric magnetic winding flux

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14. ABSTRACT

Introduction: The forecasting of solar eruptions and coronal mass ejections (CMEs) is one of the most important practical issues in solar physics. Both have crucial impacts on space weather. They occur when the magnetic field structure in the lower solar atmosphere becomes unstable. Observations suggest one of the key drivers of this instability is the emergence of complex entangled magnetic field from below the solar surface (photosphere). Reliable means of predicting these eruptions in the presence of magnetic flux emergence are a key goal in the field, but have so far proved elusive. We will develop the magnetic winding flux as predictive diagnostic of eruptive/CME events. This is a measurement of distribution of entanglement in the emerging field. Highly twisted magnetic field is a strong indicator of subsequent eruptive activity, existing diagnostics at the photosphere fail to reliably detect its presence in complex observational data. The PI and Co-I have pioneered the use of magnetic winding flux in emergence simulations to overcome this problem, showing it detects when twisted magnetic field enters the solar atmosphere. They developed code to measure the magnetic winding accurately in photospheric magnetogram data (the main source of observation of the solar magnetic field). To do so we must first overcome the uncertainty associated with observational data. We will perform a plethora of systematically varied magnetic flux emergence simulations, generating a data bank which will then be used to augment magnetic winding flux measurements obtained from the observational data. In particular this information will,
(a) establish what likely structure is missing from the observed data,
(b) assess of the level of confidence of the observational data, and
(c) assign it to a particular class of field type to allow more consistent predictive performance.
Results: This pilot study demonstrated three key scientific findings regarding the magnetic winding:
1. That the winding gave distinct but complementary information to existing metrics such as the magnetic helicity, and that this was true of observational data as well as in computational simulations [10]
2. The magnetic winding can correctly diagnose the twisted nature of of emerging active region fields, where other metrics performed inconsistently [1].
3. That flare prediction metrics derived from the magnetic winding show efficacy [2]
Dissemination:
• Aspects of the work have been published in high-impact journals and the group has two more publications planned.
• Prior, MacTaggart and Raphaldini presented aspects of this work, at the UK magnetohydrodynamics conference and the European Solar physics conference, the National astronomy meeting and the Asia-Pacific plasma physics meeting.
• The talk given by Prior at the UK national astronomy meeting was given publicity by the conference as one of its talks of the day, this was subsequently picked up in various media e.g Space Ref: http://spaceref.com/space-weather-2/unravelling-the-knotty-problem-of-the-suns-activity.html Science Daily: https://www.sciencedaily.com/releases/2021/07/210722163026.htm.
• Prior gave interviews on local radio on the work published in [1] as well as giving a video interview for the TUNDRA on Phys.org, this can be found at https://thetundra.com/conventions/beyond-space.
These results have been highly publicised and despite being published at the latter end of last year already cited by severaldistinct groups. Also, the group has published python software for automated calculation of the magnetic winding distribution of active region data sets and are currently preparing an article to highlight the functionality of this code, and will also release an interactive Jupyter notebook to further aid its dissemination (both of which will cite this funding).
References:
[1] David MacTaggart, Chris Prior, Breno Raphaldini, Paolo Romano, and SL Guglielmino. Direct evidence thattwisted flux tube emergence creates solar active regions. Nature communications, 12(1):1–8, 2021.
[2] Breno Raphaldini, Christopher B Prior, and David MacTaggart. Magnetic winding as an indicator of flare activity in solar active regions. The Astrophysical Journal, 927(2):156, 2022

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Technical report for: Developing Photospheric Magnetic Winding Inputs As A Flare Forecasting Diagnostic.

Christopher Prior (PI)
David MacTaggart (CO-I)
Breno Raphaldini (PDRA)
July 2022

Brief scientific summary

To aid the reader we first provide a very brief scientific background into the project's aims, before directly addressing the specific project accomplishments.

Background: Solar active regions, flaring and CME's

Solar active regions are regions of strong magnetic field in the solar atmosphere. They are associated with highly entangled magnetic field and often release significant energy (flaring) or bursts of plasma (Coronal mass ejections: CME's), see Figure 1. Solar flares have crucial impacts on how space weather affects critical infrastructure such as radio communication, GPS signaling and electric grids. The forecasting of solar flares is one of the most important practical issues in solar physics

Despite significant advances no current prediction method performs consistently. The study of magnetic topology: assessing the entangled structure of magnetic field, is widely recognised as a critical tool for improving flare prediction capability [4, 11–13].

Overview of proposal and prior work

The PI an Co-I had pioneered the use of the magnetic winding to measure the complexity of magnetic field structures which emerge into the solar atmosphere (see Figure 2(a) for a visualisation of the quantity's meaning). We had shown, in computational simulations, that the winding correctly diagnosed the twisted nature of the emerging active region magnetic field where other existing metrics, those used for observational studies, failed (see Figure 2(b)) [9, 14, 15]. The hypothesis underlying the project was that then existing methods for predicting solar flaring from observational data perform inconsistently as they do not always diagnose the twisted nature of the emerging field. One significant specific scientific aim of this pilot project was to see if the theoretical potential of the magnetic winding could be realised in real observational data. A second aim was to begin to develop a flare/CME prediction metric using the magnetic winding as a basis.

Accomplishments

Initial research objectives

The project abstract and goals as stated in the proposal can be paraphrased as follows:

1. To perform an extended set of magnetohydrodynamic (MHD) simulations of solar flux emergence, the emergence through the solar surface of complex twisted bundles of magnetic field which form the active regions, in order to generate the reference bank of realistic magnetogram data. The aim for this reference data bank was to use it to develop methods to overcome uncertainty in real observational data so we could accurately evaluate the real magnetic winding content of observed solar active regions.
2. To develop a code to accurately evaluate the photospheric winding flux from a time series of observed magnetograms.

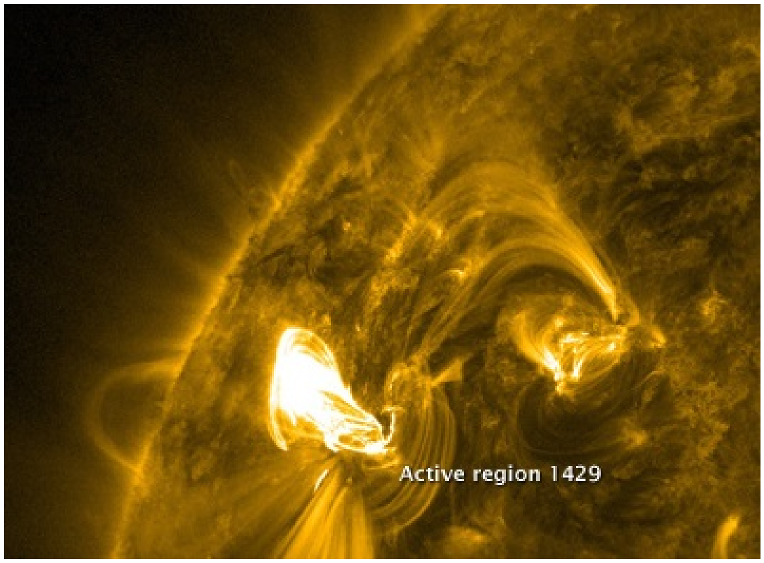
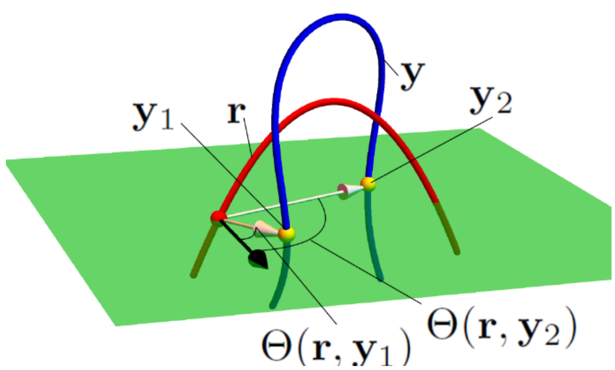
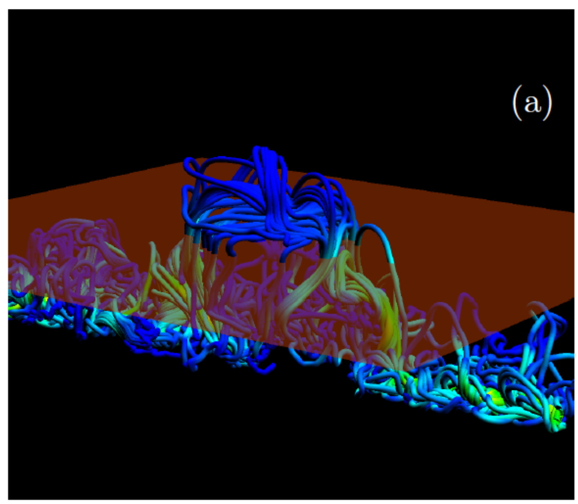


Figure 1: The flaring of a solar active region (courtesy of NASA).



(a)



(b)

Figure 2: Visualisations of the magnetic winding. Panel (a) a depiction of the magnetic winding measure, the red and blue field lines "wind" around each other, this is measured by angle functions which track this mutual rotation. Image from simulation of emerging active region formation by PI and CO-I used to demonstrate the efficacy of the magnetic winding.

3. To develop a diagnostic of the likelihood of the active region field erupting, based on the measured photospheric winding flux density in observations the use of the simulation databank to interpret this data. In particular we aimed to asses: (a) how early in its evolution the emergent field structure/topology can be determined, and (b) which aspects of its topology lead to flaring/eruption and which don't.

We stress at the outset of this report that objectives 2 and 3 were the primary scientific goals, objective 1 was a method proposed to overcome uncertainty in observational data in order to achieve them.

Proposed approach to achieving those goals

The work plans proposed for each objective can be summariesed as follows

Task A1: Perform magnetic flux emergence simulations of systematically varied flux rope entanglement [Months 1-14]

Using the set-up described in detail in the project proposal, we were to computationally simulate the emergence of a set of magnetic flux rope structures covering a range of initial complexities. The planned set of simulations was to be comprehensive enough to cover a significantly wide range of behaviours to match to observations.

For each simulation we were to calculate the magnetic winding input rates at the simulation photosphere, mimicking the observational data sets. This data could be used as a comparative "ground truth" diagnostic for comparisobns to calculations of real data.

Task A2: Calculating topological inputs for real magnetogram data [2-14 months]

Observational active region data sets were to be collected as Space-Weather Helioseismic and Magnetic Imager (HMI) Active Region Patches (SHARPS). These were obtained from the Solar Dynamics Observatory (SDO) [18] with 0".5 pixel resolution and 12 minute cadence. We were to calculate magnetic winding input distributions and test the effect of various protocols for removing noise in the data using the simulations from task A1 as a guide.

Task A3: Assessing the predictive capability of the simulation bank data [10 -18months]

Once a significant number of observational and simulation data sets were collected, the PDRA was to focus on establishing the predictive capabilities of the combination of these data sets. Previous work by the PI/CO-I indicated that the magnetic winding input distribution could discriminate different emerging field types (topologies) given the full simulation data. The question remained as to whether the loss of information would prevent this in the observational case. The idea was is that, by linking to the observational data to the much higher resolution simulation, we could make more detailed estimates of both the magnitude and nature of the topological structure of the emerging magnetic field. This assertion was to be tested in the third work plan.

If reliable methods for demising the observed magnetic winding distributions could be established, the next phase of this task was for the PDRA to develop improved diagnostic capabilities of flaring activity in a significantly large and well resolved data set.

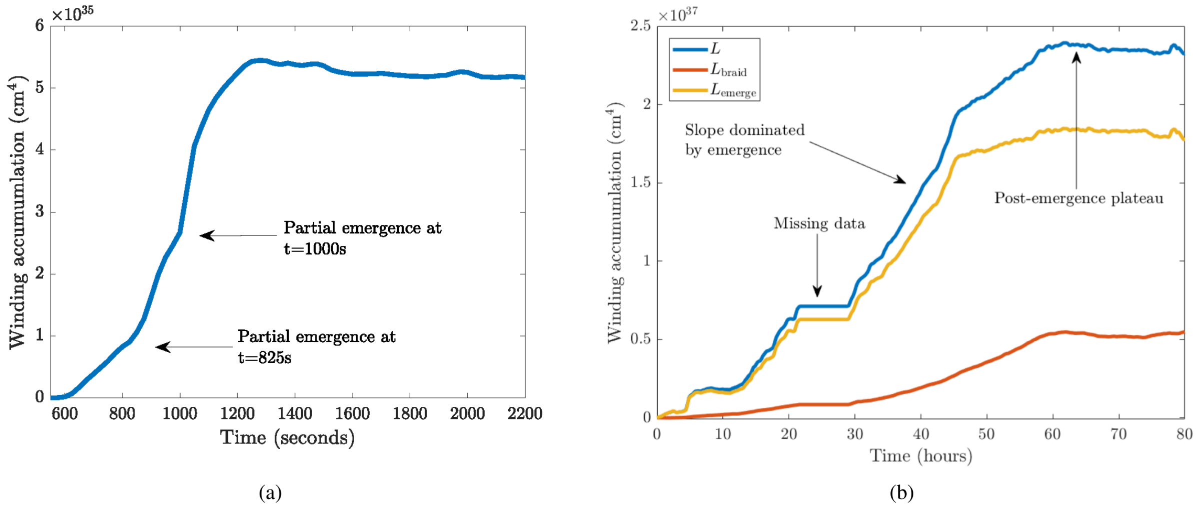


Figure 3: A comparison of theoretical and observed magnetic winding input signatures. Panel (a) A plot of the total magnetic winding accumulation, over time, in theoretical simulations of active region formation. Panel (b) observationally measured magnetic winding accumulation (blue), over time, for NOAA active region AR11318.

Specific accomplishments

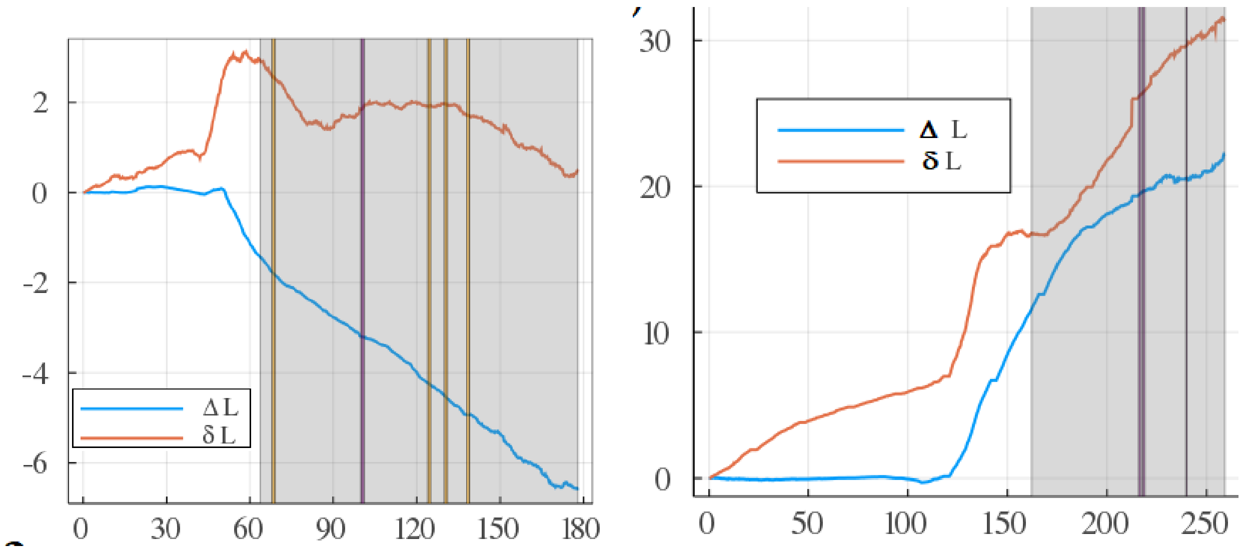
Demonstrating that the theoretical predictive efficacy of the magnetic winding carried over to real observational data.

- We demonstrated that the theoretically expected winding signature for twisted fields (Figure 3(a)) is found in observational active region data (Figure 3(b)).
- Using the proposed computational simulations of active region emergence planned for objective 1, it was shown that this signature is robust to the inherent noise in the data. This result covers aspects of tasks A1: performing flux emergence simulations, A2: Calculating magnetic winding inputs in observational data, and A3: Using simulations to interpret observational data.
- A critical aspect of the work was to demonstrate that the dominant part of injected magnetic complexity pre-existed its emergence into the solar atmosphere (as opposed to being created whilst the field was in the solar atmosphere). This answered a long standing question in the field as to how magnetic topology is dominantly created in such regions.
- This work was published in in Nature communications [10].
- As discussed in the impact section, this result received wide publicity in and outside of academia on various platforms.

This answered quite conclusively that the magnetic winding as calculated from observational data could reliably provide information about the structure of observed active region magnetic fields in the solar atmosphere.

Evidence of flare prediction capability in the magnetic winding.

- We developed a metric, δL, based on the magnetic winding, which estimates how much more current carrying field topology there is than potential (current free) magnetic topology (entanglement).
- This estimates the free energy in the system which must be high for flaring activity to occur.



(a) (b)

Figure 4: Time series of the winding based flare prediction metric δL for NOAA AR11158 (a) and NOAA AR12673 (b). The grey region covers the period where the flaring activity occurs. A significant rise in the quantity δL (the orange curve) can be seen ABOUT 20-30 hours prior to the commencement of flaring.

- We have found sudden large increases in this metric trigger flaring and CME activity in a series of active regions, see examples in Figure 4 (a) and (b), where a sharp rise in the red curve proceeds the onset of flaring by about a day.
- We have found that the rate of change of δL can be used to predict individual flaring events by approximately 7-9 hours. This is indicated in Figure 5 where measurement of the input rate of the quantity δL is seen to deviate from three standard deviations in the build up to solar flares (approximately 7-9 hours before the flare).
- We also found that regions which showed no flaring did **not** have large increases in the proposed predictive δL measure. Thus we have demonstrated a promising predictive potential of the magnetic winding.
- The initial work on this topic was published in the Astrophysical Journal [17].

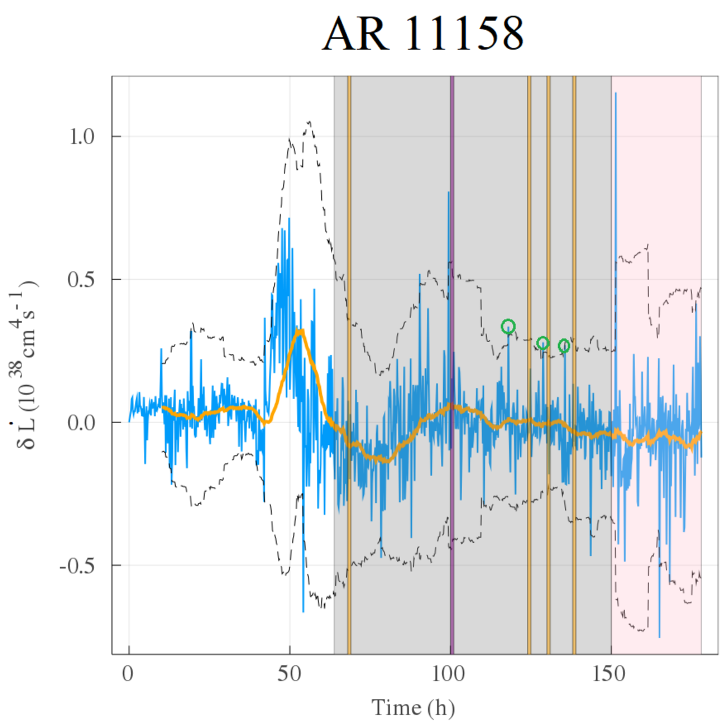
In the final part of the project we have extended this analysis to some 60 active regions (the published paper covered 5). So far the result back up these initial findings. This is neatly summarised in the fact there is a strong correlation between the maximal value of δ and the strongest flare produced by an active region, as indicated in Figure 6. We have a paper in preparation on the results of the new extended data set.

This work indicates we have achieved success in research objectives 2 (developing code to calculate observable winding inputs) and 3 developing predictive metrics for flaring/CME activity.

The production of automated software for calculating winding inputs of observed active regions and analysing this input.

We have also produced a code which performs these calculations automatically (using a maixture of c++ and python). This is available on Github: https://github.com/DavidMacT/ARTop. It has the following functionality:

- Downloading SHARP time series of solar active regions (magnetic field data).
- Calculating the corresponding plasma velocity, potential field, magnetic winding input rate distribution, and the predictive metric δL for these regions.



(a)

Figure 5: $\dot{\delta L}$ time series for NOAA AR 11158. X-class flares are highlighted with purple vertical lines, while M-class flares equal or above M intensity are highlighted in yellow. The flaring activity is indicated by the grey shading while the pink background indicates the period when the active region is situated near the limb (beyond a Carrington longitude of 60^o (outside the zone or reliability of the data). The running mean is indicated as a yellow curve and the 3.s.d envelope as dashed lines. Circles indicate the spikes where the rate $\dot{\delta L}$ is outside this envelope which can be seen to be precursors to individual flare events.

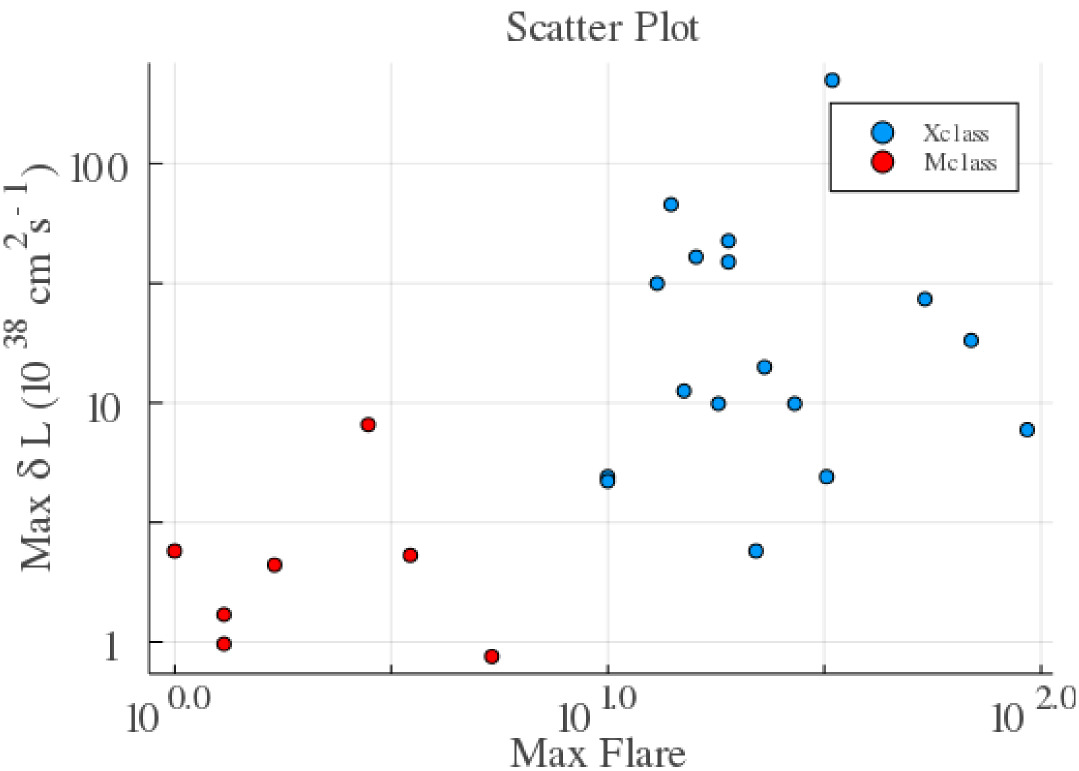


Figure 6: A Scatter plot indicating a relationship between the most intense flare and the maximum value δL (right) in X and M flare producing active regions (the strongest flare types), a positive correlation is present summarising the general relationship we have seen between significant input of the quantity δL and flaring activity.

- Plotting the spatial and temporal distributions of this data and correlating it flare data-sets such as GOES x-ray data for predictive comparison.

This code in particular is to be used as the bedrock of a proposed follow on project to this which has just been submitted to AFOSR.

Dissemination

- As mentioned above aspects of the work have been published in high-impact journals. We have two more publications planned (also discussed above).
- Prior, MacTaggart and Raphaldini presented aspects of this work, at the UK magnetohydrodynamics conference and the European Solar physics conference, the National astronomy meeting and the Asia-Pacific plasma physics meeting.
- The talk given by Prior at the UK national astronomy meeting was given publicity by the conference as one of its talks of the day, this was subsequently picked up in various media *e.g* Space Ref: http://spaceref.com/space-weather-2/unravelling-the-knotty-problem-of-the-suns-activity.html Science Daily: https://www.sciencedaily.com/releases/2021/07/210722163026.htm.
- Prior gave interviews on local radio on the work published in [10] as well as giving a video interview for the TUNDRA on Phys.org, this can be found at https://thetundra.com/conventions/beyond-space.

Impacts

This was a pilot project with primarily scientific aims (rather than a project involving a significant outreach/teaching component). So we focus primarily on the current and potential future scientific impacts of this work.

Development of the principle disciplines

As discussed above demonstrated three key scientific findings in this pilot project regarding the magnetic winding:

1. That the winding gave distinct but complementary information to existing metrics such as the magnetic helicity, and that this was true of observational data as well as in computational simulations [10]
2. The magnetic winding can correctly diagnose the twisted nature of of emerging active region fields, where other metrics performed inconsistently [10].
3. That flare prediction metrics derived from the magnetic winding show efficacy [17]

As discussed above both of these results have been highly publicised and despite being published at the latter end of last year already cited by three distinct groups [5, 6, 19]. Also, as discussed above we have published python software for automated calculation of the magnetic winding distribution of active region data sets. We are currently preparing an article to highlight the functionality of this code, and will also release an interactive Jupyter notebook to further aid its dissemination (both of which will cite this funding).

A potential follow-on project to further the work's impact.

The PI and Co-I had a white paper recently accepted by AFOSR for a follow on project to develop a live solar flare prediction software from these initial results. We have recently submitted the full funding application for this and hope this will be the means by which this work can achieve significant impact in the field of solar weather prediction.

Further potential future impacts

We believe the code we have developed will not only be used to perform flare prediction (as we described in [17]) but also to aid the solar physics community. The following are other potential uses.

To improve active-region classification

The solar physics community have developed a number of classification methods for active regions, for example the *e.g.* the Macintosh [2] or Zürich classifications [1]. These are used for flare prediction, but do not perform consistently in this task [7, 8]. These classifications based on the line of sight component of the magnetic field at the solar surface. But all the three-dimensional components are available so a more sophisticated classification should be possible. The winding takes into account all three components of the field and, as shown in [9], the winding can correctly diagnose the topological content of emerging active region magnetic fields. So we anticipate that the methods and code we have developed will be at the forefront of such future classification schemes.

To help improve dynamic boundary conditions for simulations of active region dynamics.

Simulations of the coronal magnetic field (the magnetic field in the solar atmosphere) require some assumptions as to how the electric field at the solar surface develops (boundary conditions). Often measures of the magnetic field topology such as the magnetic twist (the α parameter). This measure however is a highly noisy quantity. We anticipate the magnetic winding distributions, which do correctly diagnose the emerging magnetic twist, could be used to improve this boundary condition and hence the accuracy of the simulations.

Quantifying the topological development of magnetic fields in general.

The PI has used the magnetic winding to interpret plasma experiments performed by Professor Walter Gekelman at the UCLA basic plasma facility [3, 16]. These are fundamental experiments aimed at understanding magnetic reconnection in fusion plasmas and the release of our software will mean these tools are available to fusion plasma community.

Changes

This was a pilot project with a very specific aim, demonstrating the theoretically powerful magnetic winding metric could be accurately evaluated in observational solar active region data. More specifically that uncertainty in the data could be overcome an that the predictive efficacy found in theoretical studies could be tested on real data. As this report shows the aims were largely successful so there were few significant changes to the project. The only minor change was that the observational noise proved to be such a minor problem to the project that it was not necessary to perform the full set of computational simulations which were planned to develop methods to deal with this uncertainty. We still performed a significant number of these simulations, and they were crucial to the results of [10]. This minor change was reported to the project's program officer (Scott Dudley) in the first project update and he was happy with the changes.

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