Sunspot Rotation

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1 – Aims

Sunspot rotation is a recognised mechanism that can contribute to the energy budget of severe space weather events [1,2,3]. This work aims to better understand the energy generation properties of rotating sunspots using numerical techniques; such methods allow us to fully control a simulated rotating sunspot and remove the complexities of the real-world problem. The understanding gained from this investigation may be used, with observations of real rotating sunspots, to forecast the magnitude and time of severe space weather events.

2 - Space Weather

Severe space weather is an internationally recognised threat to our modern way of life. These events appear as "level-C" impact events in the governments National Risk Register. The register highlights that the potential economic impact of a severe space weather event could be as much as one billion pounds with many accompanying consequences. Space weather is a collective term for three main phenomena, specifically:

Coronal Mass Ejections - Coronal mass ejections (CMEs) are large eruptions from the solar atmosphere of plasma and magnetic field. They cause geomagnetic storms and power disruptions.
Solar Flares – Solar flares occur when magnetic energy is released from the solar atmosphere and often trigger other events. They release radiation that can cause radio blackouts.
Solar Energetic Particles – Solar Energetic Particles (SEPs) are fast moving particles accelerated by flares and CMEs.

3 - Sunspots and Active Regions

Figure 1 shows a small regular sunspot. Sunspots are planet sized regions where **strong magnetic fields** intersect the surface of the Sun. The magnetic field causes a cooling effect, making the **umbra** (the darkest central region) and the **penumbra** (the area surrounding the umbra) of a sunspot appear darker than the regular surface. Sunspots can exist for a month or more and in that time can rotate significantly about their centre [1,3].

Figure 2 shows an **active region**, where the grey highlights the surface of the Sun and the orange highlights the portion of the atmosphere that is traced by the magnetic field partially rooted in sunspots. These regions are where severe space weather events originate.

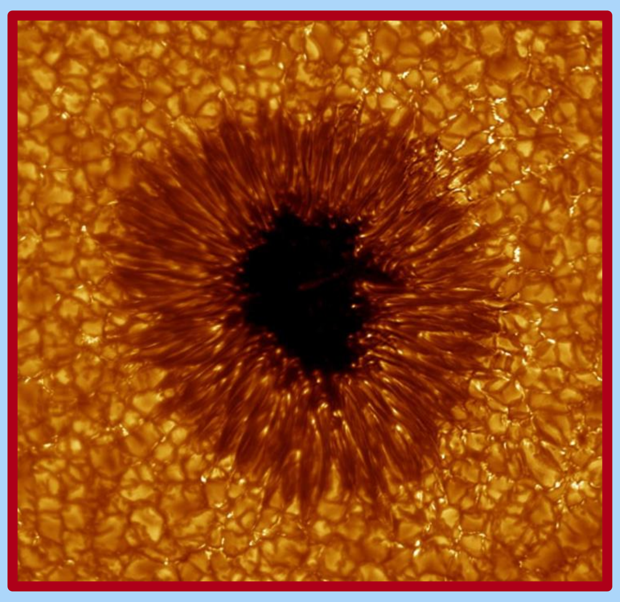

Figure 1: A small regular sunspot. Image credit: Data collected with the SST in 2002 by Göran Scharmer and Kai Langhans, ISP.

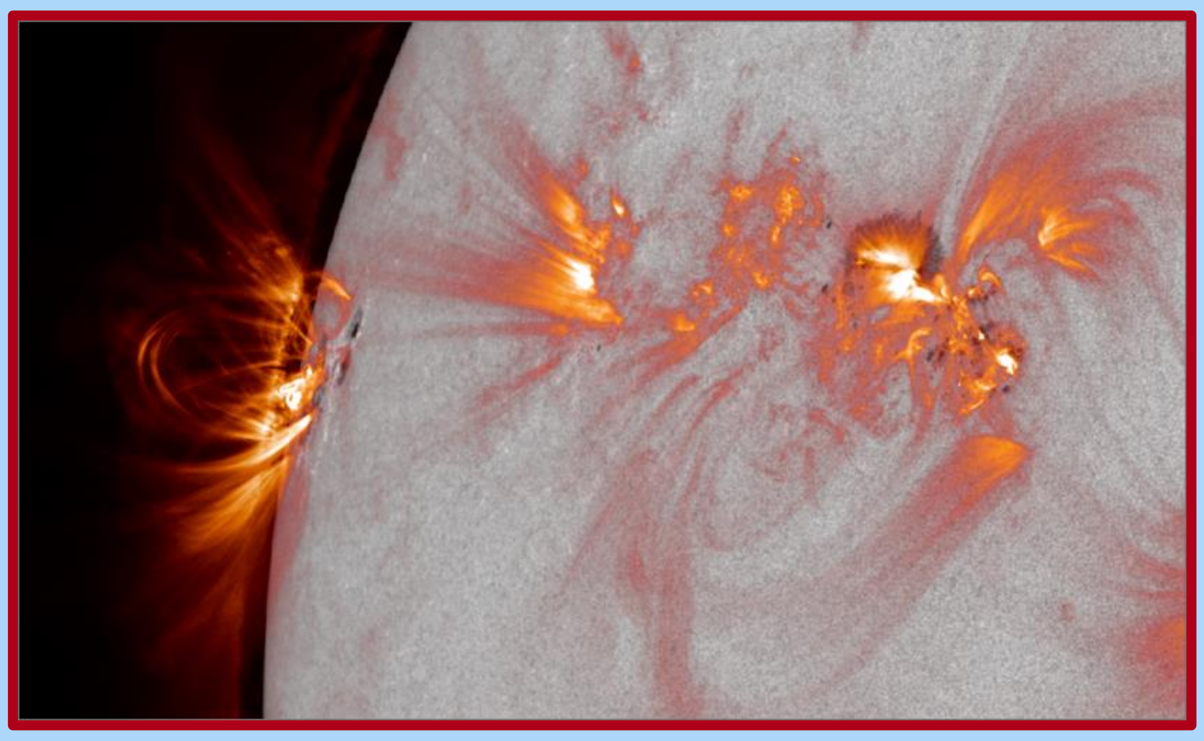

Figure 2: A composite image of a solar active region in visible (grey) and ultraviolet (orange) wavelengths.

The solar atmosphere is composed of charged gas (plasma), which causes the magnetic fields to be **frozen** into the material (causing them to move as one). This means if sunspots move, it is possible for the magnetic fields embedded in them to restructure the active region itself and potentially enhance or release the energy stored in the region.

As well as being able to transport energy, a magnetic field can store energy. It is in fact this stored **free magnetic energy** that is believed to power severe space weather events and what sunspot rotation can enhance within the magnetic field already present.

4 - Sunspot Rotation

We have derived a method inspired by the optical flow technique [4], that yields an approximation of the instantaneous velocity field of a rotating sunspot. Figure 3 displays an example of this technique, showing a sunspot and its measured velocity field.

As shown the motion in and around sunspots is very complicated, but generally when focusing on the sunspot alone one can see a counter-clockwise trend to the motion is present.

Throughout this observation, the measured velocity in the sunspot is less than its surroundings, but typically is more structured. This sunspot maintained an average rotation rate of 1.5 degrees per hour and was known to produce several large solar flares [5].

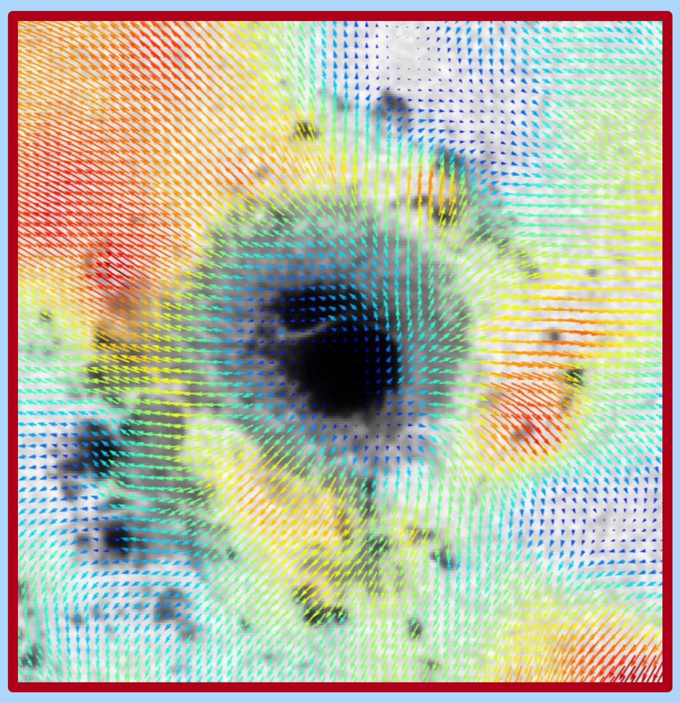

Figure 3: An image of a sunspot and satellite magnetic features with a quiver plot overlaid showing the instantaneous velocity. The colour scheme is blue-green-yellow-red, where red indicates faster movement and blue slower. The data used in this image was collected by the Solar Dynamics Observatory.

5 - Simulated Sunspot Rotation

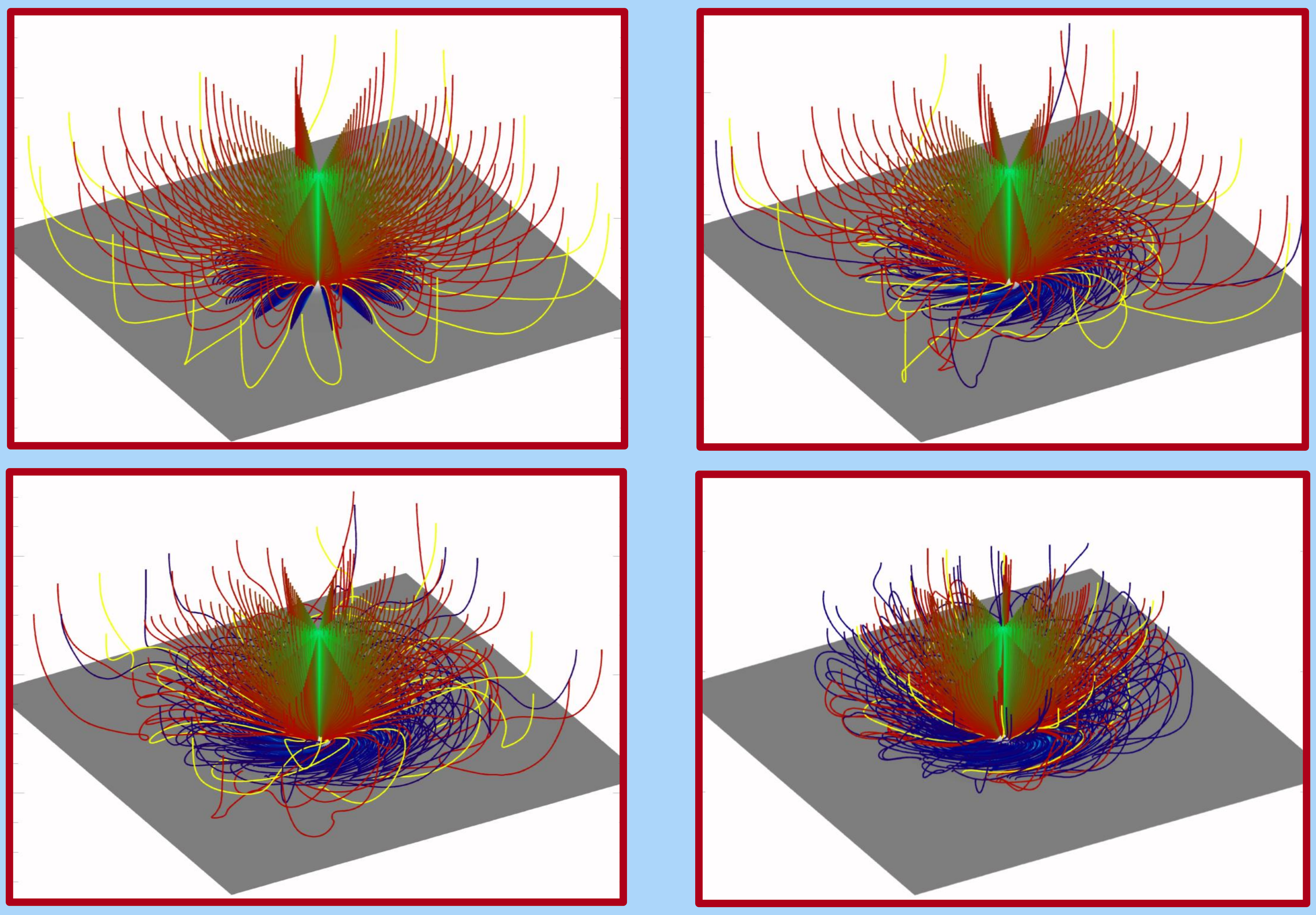

Figure 4: Four snapshot views of a simulated rotating sunspot's magnetic field. Top-left: initial sunspot, no rotation. Top-right: 90 degrees of rotation. Bottom-left: 120 degrees of rotation. Bottom-right: 150 degrees of rotation. In each figure the blue lines represent the penumbral magnetic field, and the red and green lines represent the umbral magnetic field. The yellow lines represent the boundary between the blue and red regions.

We have developed a state-of-the-art model of rotating sunspots using the Lare3d code [6]. Our numerical study investigates sunspot rotation parametrically, which means we define several parameters a sunspot must have (e.g. size, shape, magnetic field strength etc.) and simulate with these parameters fixed. Then by altering these properties individually, we can determine how each influences a sunspots ability to generate and store magnetic energy.

However, we found that despite which parameter is investigated, all simulations highlight a common theme, that the penumbra is an important region for energy generation and storage. Figure 4 shows a simulation at four stages related to the penumbra (blue lines). The penumbral field grows in volume and complexity with increasing rotation (see caption) and develops increasingly strong enveloping currents (not shown). The magnetic energy increases and is transported by the expansion. The currents formed may aid in the release of this energy as it enters the solar atmosphere.

6 - Energy Generation and Storage

Figure 5 shows the amount of energy generated and stored in the penumbral and umbral magnetic fields. The penumbra stores most of the energy and the amount of energy stored in it is sufficient to power a small space weather event.

The simulation used to produce this figure modelled a small sunspot. We find larger sunspots can generate much more energy..

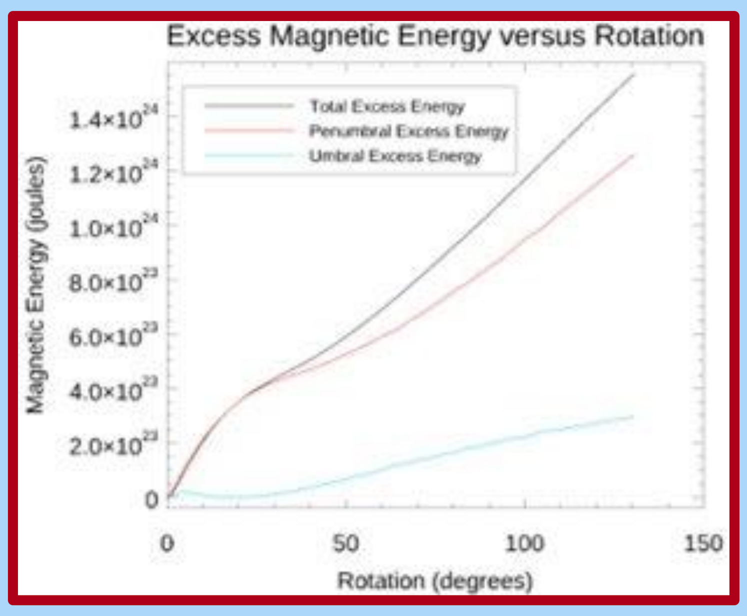

Figure 5: The magnetic energy stored in the penumbra and umbra versus rotation.

7 - Summary

We have developed a model that has provided insight into the underlying physical mechanisms responsible for powering severe space weather events. The intent of this investigation is to understand generic sunspot rotation (which we have done), but the more powerful result we find is that the penumbra is an important region for the generation, storage and transport of magnetic energy. In addition to storing energy, the penumbra forms a current sheet which may facilitate the release of its stored energy via magnetic reconnection.

References

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