Numerical Simulation of Sunspot Rotation

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Sunspot Rotation and Solar Flares

- Sunspot rotation and solar flare occurrence are believed to be linked (Brown, 2003). Figure 1 shows the rotation profiles of five sunspots in AR11158 with an accompanying flare occurrence timeline along the top. The green vertical bars represent the occurrence of a C-class flare, the blue an M-class and the red an X-class.
- It remains unclear how the characteristic physical properties of a sunspot (e.g. peak field strength, size, etc.), and the rotation itself, influences the transmission of magnetic energy into the solar atmosphere.
- We aim to establish an understanding between the physical properties of sunspots (and their rotation) and magnetic energy generation, storage and release.

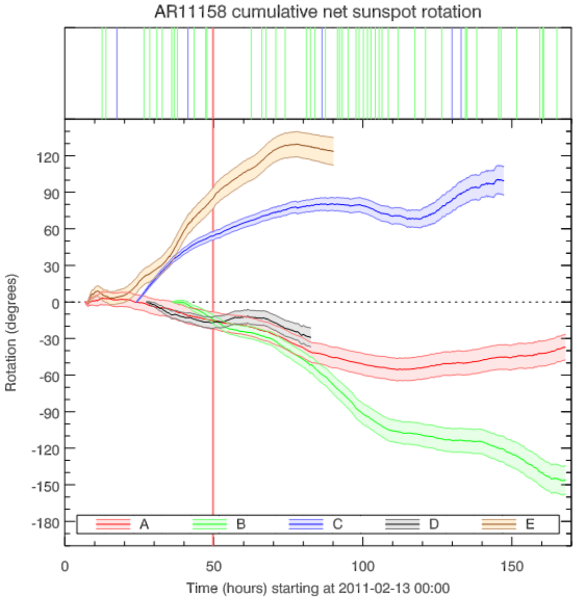

Figure 1: Image Credit: Walker (2018)

Numerical Scheme

- We use the Lare3d numerical code (Arber et al. 2001) under an ideal MHD regime.
- We initialise the simulations with a potential magnetic field that includes a closed field penumbra (blue lines in figure 2) and an open field umbra (red and green lines). The structure of the field is motivated from observations (Keppens and Martinez-Pillet, 1996) but is idealised.
- The numerical domain has a stratified density and temperature profile which mimics the atmosphere above a sunspot. The field at the top boundary is free to move.
- The sunspot is rotated at the photosphere with a solid body rotation profile for the umbra (following Botha et al. (2008)) and a cosine ramp-down to no rotation just beyond the penumbral boundary.

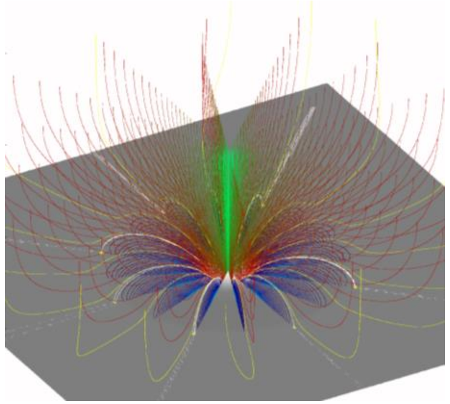

Figure 2: The initial magnetic field configuration.

Evolution of a Rotating Sunspot

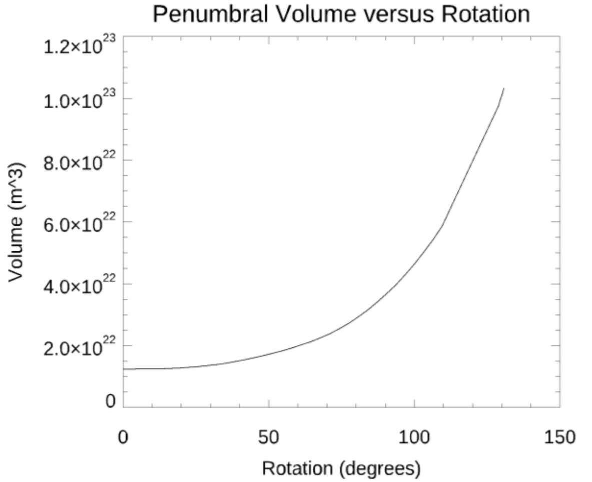

Figure 3: Plot showing penumbral volume versus rotation.

- As the sunspot rotates, the closed penumbral field expands, rises and displaces the overlying, open, umbral field. The penumbral field continues to rise and reaches the top of the domain.

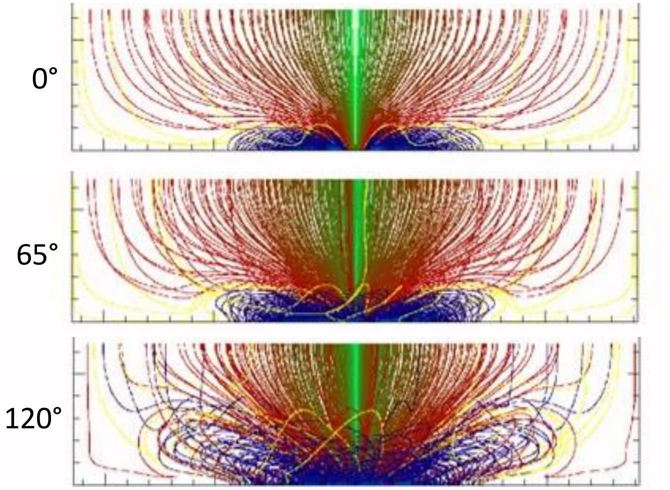

Figure 5: Three side-on views of the magnetic field of the sunspot at 0°, 65° and 120° rotation.

- The sunspot is accelerated from rest with a sinusoid acceleration profile; reaching a maximum rotation rate at ~32°.
- The acceleration introduces an energy contribution from the Euler Force which is stored in the penumbral field. This dissipates by ~50° (shown in figure 4).
- During the phase of constant rotation, there is a constant additional energy contribution from the centrifugal force. We find a sunspot rotating at 48°/hr gains ~5% additional magnetic energy compared to a sunspot rotating at 6°/hr.

Energy Storage in the Penumbra

- The freely rotating (open) umbral field stores only a small amount of the total injected magnetic energy.
- The closed penumbral field is found to be able to both store injected magnetic energy but also transport it into the corona as a consequence of the penumbral expansion.

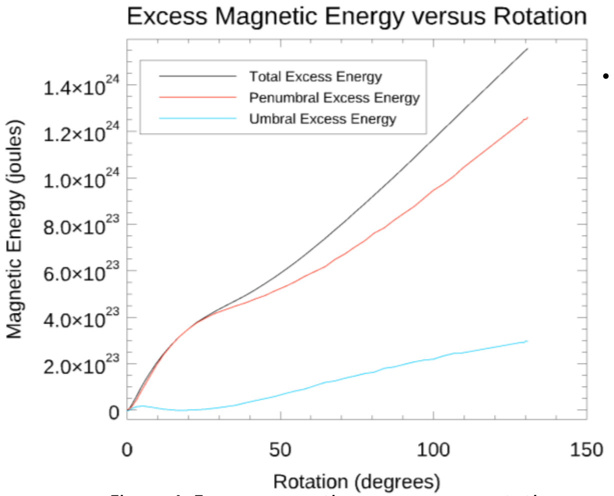

Figure 4: Excess magnetic energy versus rotation.

References

- Arber, T. D. et al (2001), JCP 171(1), 151–181.
- Botha, G. J. J. et al (2008), MNRAS 387(4), 1445–1462.
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