SOLAR PHYSICS

When the tail wags the dog

Solar eruptions are triggered by magnetic stress building up in the corona due to the motion of the Sun's dense surface. New observations reveal that these eruptions can, in turn, induce the rotational motion of sunspots.

Guillaume Aulanier

The Sun's corona is an electrically conducting fluid embedded in strong magnetic fields. Solar eruptions are triggered in the corona, and the most violent ones are associated with sunspots. Before an eruption occurs, free magnetic energy must accumulate in the corona in the form of shear and twist in the lines of force. This is just like a string twisted along its whole length by fingers winding the ends. The deformations of coronal field lines are the direct result of the motion of the dense underlying photosphere. A typical example of solar surface motion that eventually leads to eruptions is sunspot rotation: both theory[1–3] and observations[4,5] suggest that sunspot rotation leads to eruptions.

However, "in astrophysics, it never works as we expect — often the contrary", as I was taught by one of my best astrophysics professors (J.-P. Chièze, 1950–2015). Writing in *Nature Communications* Chang Liu and colleagues[6] report observations that unambiguously show how solar flares induce differential rotation of sunspots — yet another example that corroborates this statement.

The idea that the coronal eruptions can cause sunspot rotations is like imagining that the accumulated stress in the aforementioned string could force one's wrists to twist. Or imagining that a hurricane in Earth's atmosphere could induce a large-scale whirlpool in the ocean. Impossible? And yet, long-duration increases of the Lorentz forces within sunspots right after eruptions have been recently reported[7,8]. These studies were made possible thanks to increasingly available photospheric vector magnetic field measurements from new-generation telescopes such as those onboard both the Hinode and the Solar Dynamics Observatory spacecraft.

Thus far, attention has mostly been focused on relating these forces to observed changes in the magnetic field vector inclination between sunspots from nearly vertical to horizontal. The combined measurements have been interpreted as a signature of the low-altitude downward collapse of magnetic loops, either due to momentum conservation associated with the upward-moving eruption[7] or the decrease of magnetic stress in the sheared and twisted coronal fields[8]. The same possible causes are now invoked for the coronal origin of horizontal rotational motion in sunspots[8].

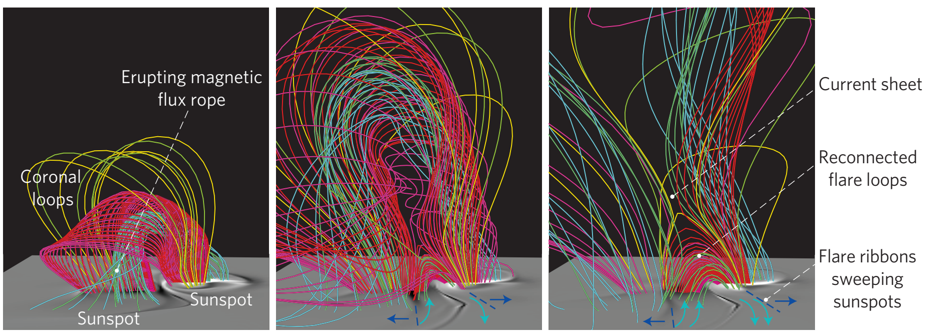

Figure 1 | Typical features of a solar eruption that are linked to the location and timing of flare-induced differential rotation within sunspots. Series of snapshots, from left to right, of a realistic numerical simulation of an eruptive flare. The simulation was achieved in the pressureless, line-tied and resistive magnetohydrodynamics regime using 375 × 375 × 336 mesh points, with a similar set-up to that used in recent flux-cancellation models[3]. In all panels, the coloured lines show representative coronal magnetic field lines plotted from fixed footpoints in the photosphere: the cyan field lines represent the erupting flux rope, and the red (green) field lines are those that eventually reconnect with pink (yellow) field lines. The greyscale plane shows the time-varying electric current densities in the photosphere. Modelled flare ribbons are mimicked by elongated current concentrations[9], and their positions are highlighted by blue dashed lines. The blue arrows show the displacement of the ribbons and cyan curved arrows indicate how sunspot rotation is initiated as flare ribbons move across sunspots[6].

However, to establish a clear and causal picture, each of these conjectural interpretations of flare-induced sunspot rotation should be addressed one after the other, and their physical mechanisms should be specified and quantified. First, magnetohydrodynamics tells us that changes in the magnetic field inclination are allowed, even in the non-moving photosphere, when coronal flows such as a downward collapse are present. But it is unclear how these changes can in turn generate photospheric horizontal flows in general, and sunspot rotations in particular. Second, it is unclear whether solar eruptions, which propagate in the diluted corona, can actually affect the dense photosphere itself by conservation of momentum. At this stage, more details about how sunspots rotate and how the magnetic field is restructured during solar eruptions are required to try to understand how the tail can wag the dog.

Let us start with eruptions, which usually comprise several coupled phenomena. Each eruption involves a twisted magnetic flux rope that is accelerated away from the Sun up to Alfvénic speeds, eventually becoming a coronal mass ejection (CME). The fast stretching of magnetic loops in the wake of the CME leads to the rapid formation of an elongated electric current sheet, which initiates magnetic reconnection. Particles are then accelerated along the magnetic field lines, and the subsequent impact of these particles in the underlying dense layers of the Sun produces brightenings, detectable at almost every wavelength. They constitute a solar flare (distinct from the CME). Of particular interest are bright flare-ribbons that occur at the footpoints of the evolving boundaries between pre- and post-reconnected magnetic field lines. As reconnection proceeds, field lines that are spaced further and further apart reconnect and turn into shorter flare loops, so flare ribbons sweep the Sun's surface during a flare. This is the standard picture for eruptive flares[9] (Fig. 1).

The key result reported by Liu and co-workers[6] is that sunspots do not rotate as a whole when the eruption begins. Instead the rotation starts at one side and gradually spreads across the whole sunspot. This moving front of rotation, which is reminiscent of a wave, actually corresponds to a flare ribbon that sweeps the sunspot. This implies that surface rotations are probably not directly induced by the dynamics and momentum of the CME, but are a direct consequence of the flare reconnection that proceeds in the corona.

From there we can only speculate. Sheared flare-loops may still be out of force-free equilibrium after reconnection. Shear Alfvén waves may then be launched downwards from the loop tops, and later initiate large-scale coherent horizontal motions of the loop footpoints within sunspots. Testing this idea — which is possible (in principle) given the fact that line-tying is not completely efficient in the photosphere[10] — would require extended and quantitative studies. More generally, the physical understanding of how solar flares can induce sunspot rotation as observed by Liu and colleagues[6] is a challenge that will presumably drive many new instrumental and theoretical investigations in the field of solar flare research. ❐

Guillaume Aulanier is at the Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92190 Meudon, France.
e-mail: guillaume.aulanier@obspm.fr

References

1. Török, T. *et al. Sol. Phys.* **286,** 453–477 (2013).
2. Amari, T., Canou, A. & Aly, J.-J. *Nature* **514,** 465–469 (2014).
3. Zuccarello, F. P., Aulanier, G. & Gilchrist, S. A. *Astrophys. J.* **814,** 126 (2015).
4. Brown, D. S. *et al. Sol. Phys.* **216,** 79–108 (2003).
5. Tian, L. & Alexander, D. *Sol. Phys.* **233,** 29–43 (2006).
6. Liu, C. *et al. Nat. Commun.* **7,** 13104 (2016).
7. Fisher, G. H. *et al. Sol. Phys.* **277,** 59–76 (2012).
8. Petrie, G. J. D. *Astrophys. J.* **759,** 50 (2012).
9. Janvier, M., Aulanier, G. & Démoulin, P. *Sol. Phys.* **290,** 3425–3456 (2015).
10. Ofman, L. *Astrophys. J. Lett.* **568,** L135–L138 (2002).