Press release

Solar eruptions are continuously eroded and regenerated

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Reaching a better understanding of coronal mass ejections (CMEs) and their connection to the Sun's surface is a major stake for space weather. Using state-of-the-art numerical simulations and space observations, a team of scientists from Paris Observatory - PSL and from the Astronomical Institute of the Czech Academy of Sciences discovered that, while CMEs propagate throughout the heliosphere, their core is continuously eroded and rebuilt all together, resulting in a drifting of their anchorage at the Sun's surface. This unprecedented mechanism, that renews the historical standard model, is described in a series of articles published between January and December 2019 in Astronomy & Astrophysics and in the Astrophysical Journal.

Solar flares are the most violent manifestations of solar activity. They are characterized by a sudden and intense increase in light emissions at all wavelengths. Many of them are accompanied by a coronal mass ejection (CME), during which part of the outer atmosphere of the Sun - the corona - is ejected into interplanetary space. When they reach Earth, CMEs can have a major impact on our technology. Understanding their connection from the Sun to Earth is therefore of major importance for space weather.

At the core of a CME lies an ensemble of twisted magnetic field lines, called a magnetic flux rope. Like classic coronal loops, as observed on all solar images in extreme ultraviolet (EUV), the twisted rope forms an arch that threads the corona and that is anchored to the Sun's surface at both ends. When a solar flare occurs, the flux rope escapes from the Sun and causes a large-scale reorganization of the coronal magnetic field, with a change in the connections of the magnetic field lines: this is the well-known phenomenon of magnetic reconnection, which is accompanied by an abrupt release of magnetic energy observed in the form of a burst of light, the flare.

The team of researchers from Paris Observatory and from the Astronomical Institute have discovered that reconnection does not only occur between pairs of classic loops, and below the eruptive flux rope where it is observed regularly and long since described by the standard model, but also at the feet of the rope itself.

This process, never described before, is causing peculiar changes in the nature of magnetic field lines that were previously not considered. In particular, through reconnection, some classic coronal loops can transform into flux rope field lines, while certain twisted magnetic field lines from the rope turn into hot post-flare loops, that are the brightest in EUV and X-rays. For the very first time an explanation is proposed for the formation of post-flare loops located at the two extremities of the flare arcade, which until now were merely thought to be formed within the framework of the standard model.

Another significant consequence of this new process is that this reconnection jointly erodes and regenerates the flux rope on both sides of each of its two extremities. This continuous recycling of the eruption leads to an unexpected behavior for the CME: its anchor points at the surface of the Sun must be drifting during the eruption, a feature which is absent from the standard model. "Solar flares are like a kind of phoenix, whose feathers would grow continuously on the back of its wings while others would be consumed below", says Dr. Jaroslav Dudík of the Astronomical Institute of the Czech Academy Sciences.

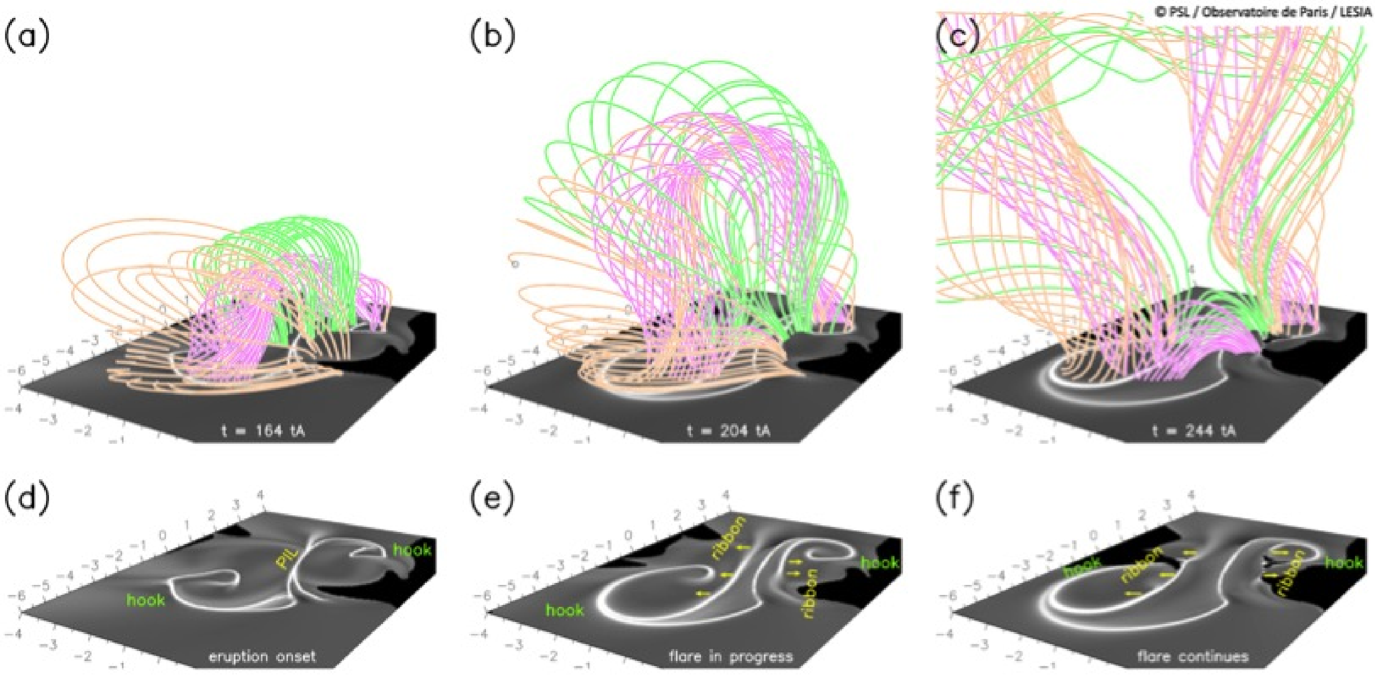
This discovery was achieved through tightly-coupled numerical and observational works. One the one hand, the researchers used a three-dimensional magneto-hydrodynamic model, that has been developed during several years by Dr. Guillaume Aulanier and coworkers at the Paris Observatory, based on numerical simulations using the parallel computer MesoPSL of the university Paris Sciences & Lettres. On the other hand, they applied original methods for data analysis, as developed by Dr. Dudík and his team from the Astronomical Institute of the Czech Academy of Sciences, which they applied to space observations from NASA's Solar Dynamics Observatory satellite.

The coupling between both approaches was achieved by making refutable model predictions, and by testing them by observations. The focus was brought on flare loops and ribbons, the latter being conspicuous elongated brightenings, sometimes displaying a hooked shape. In short, "if you see ribbon hooks moving, and flare loops appearing where the hooks used to be, that means that the anchor points of the erupting flux rope are drifting", says Dr Aulanier, who adds "that can only be explained by the new reconnection geometries that we discovered in 3D, and that is a clear-cut signature of the displacement of the anchorage at the Sun's surface of CMEs while they propagate throughout the heliosphere".

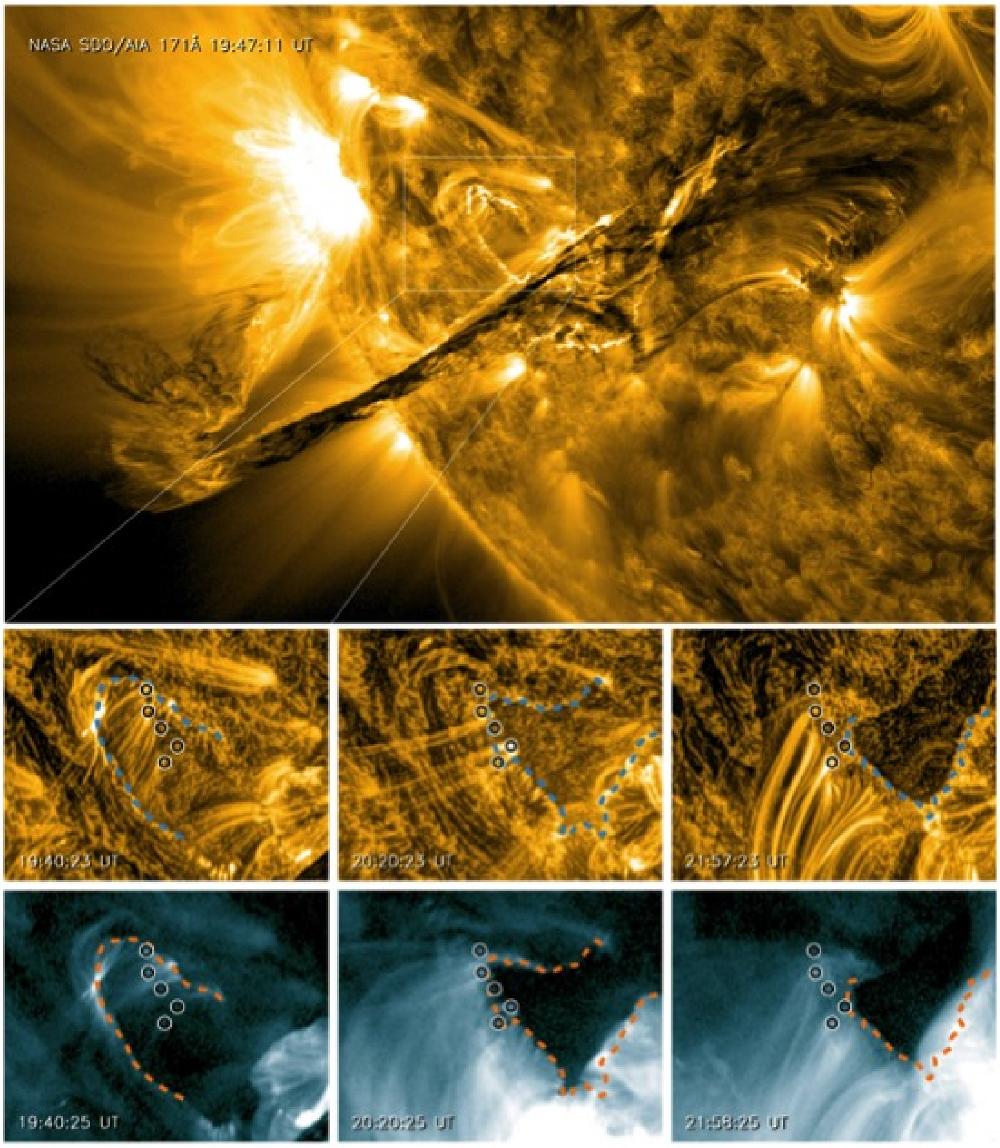
The outcome of testing the model predictions was not obvious. It required analysis of several observed flares, with a major effort to highlight usually-overlooked features. "Flares are very complex, in some you only see the drift of the hooks, while in others you see the erupting flux-rope itself", says Dr. Dudík of the Czech Academy of Sciences, who coordinated the observational analyses.

One of the flares, analyzed by Juraj Lörinčík, a PhD student of Dr. Dudík, is the famous filament eruption of August 31, 2012. By performing multi-wavelength analyses and thermodynamic calculations, Mr. Lörinčík unveiled for the very first time that, as the ribbon hook evolves, it sweeps the filament footpoints and turn them into flare loops. Exactly as predicted by the model. "The hooks, which have long been ignored in observations of solar eruptions, play an important role in evolution of these fascinating phenomena", says Mr. Lörinčík. "Now, we have seen for the first time that the reconnection in flares is much richer and varied than previously thought."

These findings have consequences for space weather predictions. "We just found out that the CME flux rope that propagates into the heliosphere is not the same as the one that erupts from the Sun", says Dr. Aulanier "so we need to invent new ways of characterizing the recycling of interplanetary CMEs, possibly by looking at their changing solar footprints". ESA's Solar Orbiter mission, which is about to be launched in February 2020, will be perfectly suited for this, given its unprecedented suite of coupled in-situ and remote-sensing instruments.



Numerical simulation of the early phases of a solar eruption. (Top row:) The original flux rope, in pink, is gradually eroded on its right side; and it is being rebuilt on its left side from coronal loops, in orange. Also shown are classical coronal loops, in green, that reconnect as described by the standard flare model. (Bottom row:) The hooked flare ribbons, in white, surround the moving anchor points of the erupting flux rope, and drift away from their original positions. © *Observatoire de Paris - PSL / LESIA*



The solar eruption of August 31, 2012 as observed in the EUV by the Solar Dynamics Observatory satellite. (Top row:) Full-view of the event in 171 Angstrom. (Middle row:) Close-up on the evolution of the leftmost hooked-shaped ribbon and erupting filament loops. (Bottom row:) Close-up in 94 Angstrom on the formation of hot flare loops. © *NASA / SDO / Astronomical Institute of the Czech Academy of Sciences*

References :

- Aulanier, G., Dudík, J.: 2019, "Drifting of line-tied footpoints of CME flux-ropes", Astronomy & Astrophysics, 621, A72 (13 pp.)
- Zemanová, A., Dudík, J., Aulanier, G., Thalmann, J. K., Gömöry, P.: 2019, "Observations of a Footpoint Drift of an Erupting Flux Rope", The Astrophysical Journal, 883, 96 (13 pp.)
- Löriník, J., Dudík, J., Aulanier, G.: 2019, "Manifestations of Three-dimensional Magnetic Reconnection in an Eruption of a Quiescent Filament: Filament Strands Turning to Flare Loops", The Astrophysical Journal, 885, 83 (11 pp.)
- Dudík, J., Löriník, J., Aulanier, G., Zemanová, A., Schmieder, B.: 2019, "Observations of all pre- and post-reconnection structures involved in three-dimensional reconnection geometries in solar eruptions", The Astrophysical Journal, 887, 71 (8 pp.)

