MATHEMATICAL MORPHOLOGY APPLIED TO SOLAR FEATURES DETECTION

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Introduction

The visible features on the Sun may reveal aspects of the magnetic state of our star. Indeed, strong magnetic fields can enhance solar activity and may power large solar eruptions. These solar eruptions may then interact with Earth, sometimes with a significant impact on our technosphere. They can damage radio communication, facilities in space and on Earth, or even threaten the health and life of astronauts and aircraft passengers traveling at high latitudes. Thus, in our increasingly technology-driven world, there is now an urgent need to be able to better forecast *Space Weather*, the conditions describing the interactions between Earth and the non-static Sun.

I – The Mathematical Morphology (MM) method

- Proposed in 1964 by G. Matheron and J. Serra (Soille (1999))
- Based on set theory, topology and integral geometry
- **Particularly suited to solar image processing** (Barata *et al.* (2018)) as it:
  - Deals with the geometry of complex and irregular shapes and recognizes sharp edges
  - Extracts quantitative features (e.g., area, length, sinuosity, etc.)
  - Is not affected either by the limb darkening effect or by the atmospheric and meteorological effects that may appear on images taken by ground-based observatories

II – MM applied to sunspots and faculae detection

- We detect faculae (or facular regions) and sunspots with MM algorithms over the entire solar cycle 24 in images taken at the Observatory of Catania, Italy.
- In Figure 1, left panel, we identify faculae in a ground-based observatory chromospheric image.
- In Figure 1, right panel, we find sunspot contours in a satellite photospheric image.

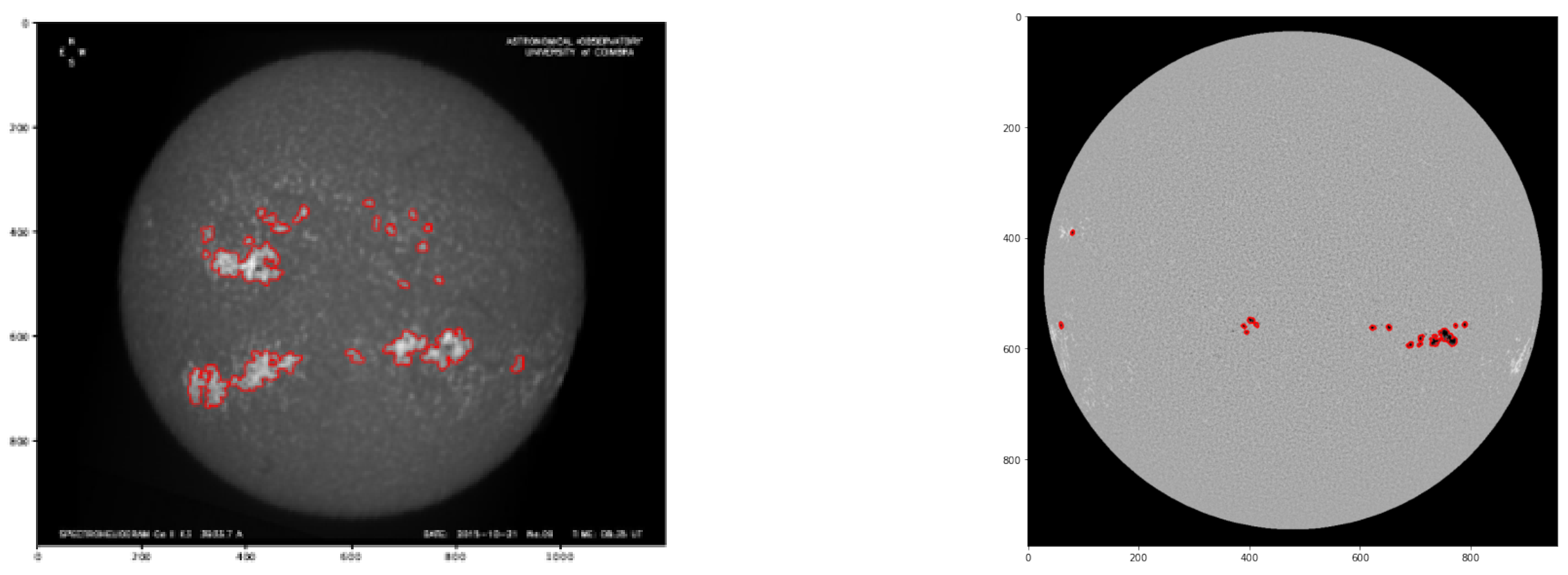

Figure 1: On the left: Facular regions detection with MM in a spectroheliogram taken at the Observatory of Coimbra, Portugal. On the right: Sunspots identification with MM in a *Solar Dynamics Observatory* (SDO)/*Helioseismic and Magnetic Imager* (HMI) intensity image.

III – Validation of the MM method

- We measure the projected areas of the contoured sunspots.
- We compare these areas with established solar catalogues, such as the *Debrecen Heliophysical Observatory* (DHO) and Mandal, Sudip *et al.* (2020) databases.
- We consider the *foreshortening effect* = projection effect making the apparent size of the sunspots near the limb appears smaller than it actually is.
- Table 1 shows good correlation between the MM method and the other catalogues, both in terms of projected and corrected areas.

Table 1: Correlation coefficients between the different area catalogues.

Correlation coefficient	Corrected Areas	Projected Areas
MM/DHO	0.91	0.95
MM/Mandal, Sudip *et al.* (2020)	0.88	0.96
DHO/Mandal, Sudip *et al.* (2020)	0.93	0.97

IV – MM applied to delta-sunspots identification

- By combining both types of segmented images presented in Figure 2, we can find the so-called delta-sunspots.
- *Delta-sunspots* = sunspots with umbrae of different magnetic polarities inside the same penumbra.
- Delta-sunspots are strongly correlated with the onset of the most powerful X-class solar flares (Robertus, Erdélyi (2022)).

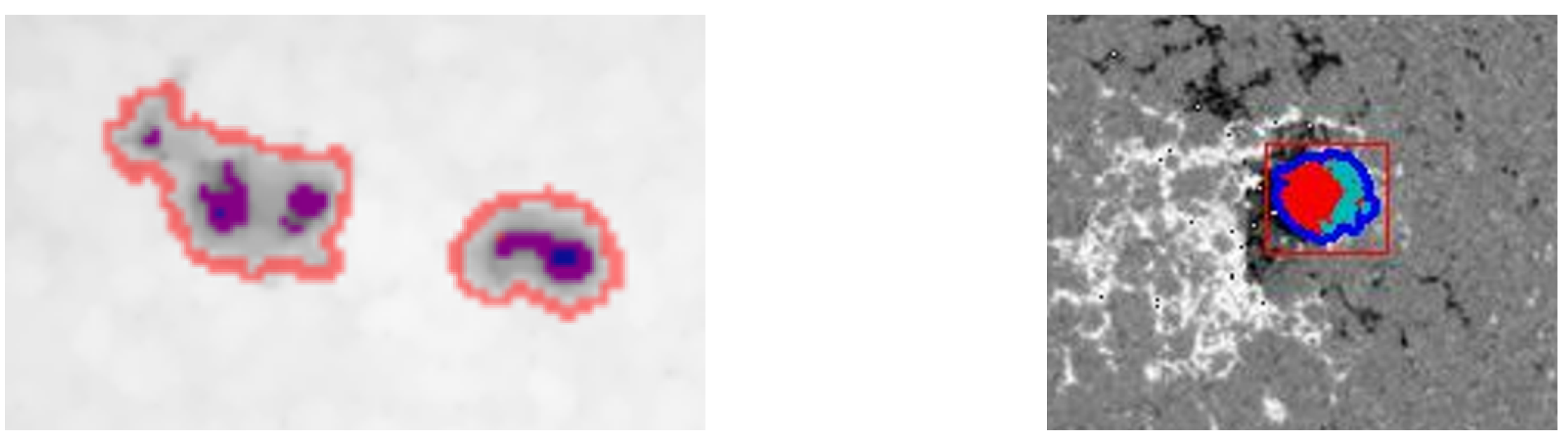

Figure 2: On the left: Segmentation of the penumbra (in red) and the umbra (in blue) in an SDO/HMI intensity image with MM. On the right: Superposition of sunspots contours (in blue) over an SDO/HMI magnetogram. The positive polarities are shown in turquoise, while the negative ones are in red.

V – MM applied to Flux Rope (FR) extraction

- We also can apply MM to simulation data, as shown in Figure 3.
- After extracting the FR with MM from a twist number map, we model the evolution of the FR's magnetic footpoints.
- We investigate the evolution of the FR's properties (e.g., average twist, cross-section area, circularity, etc.)

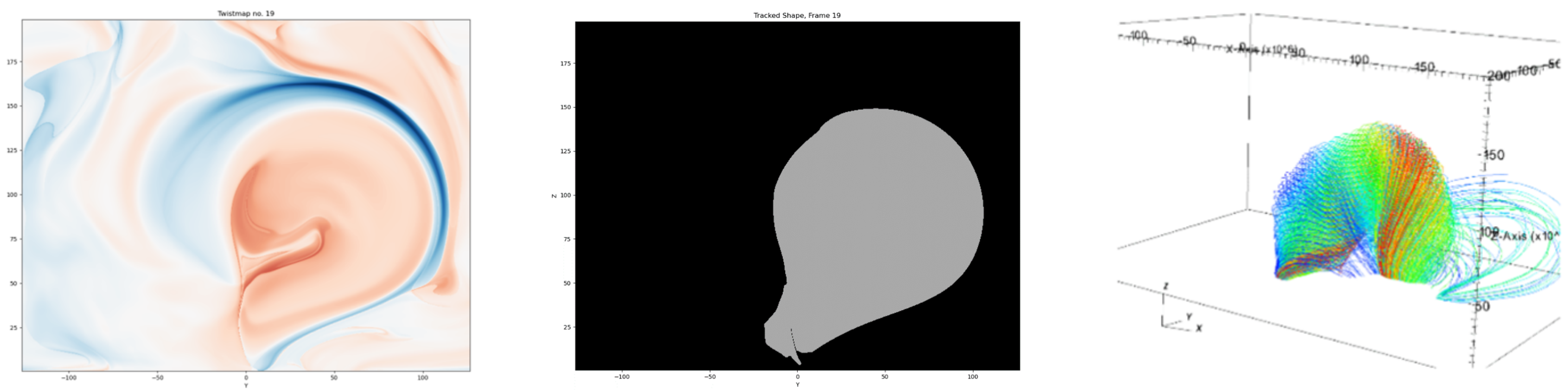

Figure 3: On the left: Twist number map obtained from a time-dependent magnetofrictional code taking SDO/HMI magnetograms as boundary condition. High intensity colours indicate regions with high twist values, red for positive twist values, blue for negative twist values. On the middle: Extraction of the FR from the twist map with MM. On the right: Visualisation of the FR's magnetic field lines after extraction.

Conclusion

- The MM method successfully **finds contours of sunspots and faculae** in different types of solar images from low-resolution (i.e., spectroheliograms from ground-based observatories) to higher resolution (e.g., SDO intensity images) over a solar cycle.
- The MM method can also be applied to simulation data for **FR extraction**.

Future work

- Determine the delta-sunspots and the *Polarity Inversion Line* (PIL) separating the different magnetic polarities inside the delta-sunspots.
- Investigate the correlation between PIL's properties (e.g., length) at different heights in the solar atmosphere and the eruptivity of X-class solar flares.
- Investigate the underlying triggers of a FR's instability: what properties ultimately lead to an eruption?

References

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