## Project title:

## Instrumentation at the forefront of solar physics: probing sunspot dynamics at the highest resolutions


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**Helpful Existing Knowledge:**
The Sun is one of the most important astronomical objects for humankind, with solar activity driving "space weather" and having a profound effect on the Earth's environment. It provides a unique laboratory where the study of interacting plasmas with concentrated magnetic fields can be readily achieved over an enormous range of scales. A large fraction of the phenomena that exists in the dynamic layers of our Sun is intrinsically linked to the strong magnetic fields that permeate through its entire atmosphere. It is believed that the building blocks of large-scale atmospheric structuring are present at the base (photosphere) of the solar atmosphere, and that these structures unlock the mechanisms that promote efficient energy transfer through the Sun's layers. A prime example are sunspots, which create towering coronal loop structures extending many hundreds of thousands of km away from the visible solar surface.

The powerful magnetic fields that are embedded within sunspot atmospheres provide an efficient mechanism to channel magnetoacoustic wave motion from below the solar surface up into the dynamic layers of the outer atmosphere (Jess et al. 2023a). Furthermore, many of the sunspots observed appear to have distinct eigenmodes, whereby the entire sunspot is observed to oscillate coherently with the same frequency. Why is this? What underlying physical mechanisms allow for a structure much larger than the Earth to oscillate uniformly across its entire surface? The challenge is to understand how both (1) the shape of the sunspot, and (2) its plasma composition with atmospheric height produces the signatures we see in the observations. For example, do sub-surface drivers fuel the eigenmodes we observe? Or do waves trapped in a solar resonance cavity (similar to that of an acoustic guitar) provide the creation of these powerful effects? In order to probe such plasma effects at the diffraction limit of high-resolution telescopes requires the use of novel imaging techniques, along with theoretical interpretation of the observed wave signals (e.g., Stangalini et al. 2022).

**Project Description:**
The project will combine observational, theoretical, computational and statistical techniques in a fast-paced academic environment. Recently, QUB researchers commissioned a novel new instrument on the Dunn Solar Telescope in New Mexico, USA, called the Fibre-Resolved opticAl and Near-infrared Czerny-Turner Imaging Spectropolarimeter (FRANCIS; Jess et al. 2023b), which is able to capture spatial and spectral information simultaneously. During a recent observing campaign in July 2025, we obtained millions of spectral images at high temporal cadences (tens of frames per second), with many observations sampling large-scale sunspot structures. The PhD student will be the first person to examine these pioneering data and will develop advanced wave detection and tracking algorithms to characterise and ultimately understand the behaviours, energetics and roles magnetohydrodynamic waves play in the creation of coherent oscillations in sunspot atmospheres. Such techniques may include longitudinal analysis, three-dimensional Fourier filtering, non-local de-noising, among others,

to best improve the dynamic range of the observed signals, while maintaining photometric accuracy (e.g., Jafarzadeh et al. 2025). It is anticipated that the timely nature of this project will position the student in an ideal position to make new discoveries and drive forward research in astrophysical disciplines.

In addition, the student will be encouraged to become involved with imminent upgrades to FRANCIS, including the addition of polarisation optics to allow the instrument to infer magnetic field information alongside its spectral imaging capabilities, which is expected to take place in 2026/27. Hence, the project will require a student who is interested in instrument development, large-scale data analyses, and uncovering novel results that are at the forefront of current research efforts in solar physics. If successful, funding will be provided within the PhD studentship for travel to, and participation in, key astrophysics conferences throughout the project. It is envisaged that the student will actively engage in both national and international meetings and workshops, where they will disseminate their cutting-edge research to a global audience. As a result, the ability to travel and work within a team environment is a crucial component of the research objectives.

**Useful references**

Jafarzadeh, S., Jess, D.B., Stangalini, M., Grant, S.D.T., Higham, J.E., Pessah, M.E., et al. 2025, *Nature Reviews Methods Primers*, **5**, 21 (doi:10.1038/s43586-025-00392-0).

Jess, D.B., Jafarzadeh, S., Keys, P.H., Stangalini, M., Verth, G. & Grant, S.D.T. 2023a, *Living Reviews in Solar Physics*, **20**, 1 (doi:10.1007/s41116-022-00035-6).

Jess, D.B., Grant, S.D.T., Bate, W., Liu, J., Jafarzadeh, S., Keys, P.H., et al. 2023b, *Solar Physics*, **298**, 146 (doi:10.1007/s11207-023-02237-z).

Stangalini, M., Verth, G., Fedun, V., Aldhafeeri, A.A., Jess, D.B., Jafarzadeh, S., et al. 2022, *Nature Communications*, **13**, 479 (doi:10.1038/s41467-022-28136-8).