Opening pupils' eyes to

Ryan French and colleagues discuss their Hinode/EIS outreach work and the resulting resources available for A-level classes.

As the only star resolvable to more than a few pixels, the Sun acts as an astrophysical laboratory, providing insight into plasma processes on energy levels from black holes to the aurora. Many of these key areas of physics are introduced in the UK's A-level curriculum, from atoms and electromagnetic waves to astrophysics and cosmology. However, due to the nature of the curriculum, A-level students are rarely exposed to active research. Without this exposure, science can seem like a "finished product", as opposed to an iterative process of ongoing work. This can produce damaging stereotypes of science/scientists and lower student engagement with science.

Here we discuss how engaging A-level students in solar physics data analysis can be used to apply and consolidate content from the A-level curriculum, while providing the opportunity to analyse original data and engage in current research. Involving students with research in this way has been shown to improve student engagement with science, and aid in reducing damaging stereotypes (Bennett *et al.* 2016).

This article provides an overview to the educational coding resources we used to do this, and provides a case study of first-year A-level students (aged 16–17) at St Wilfrid's Catholic School in Crawley, who helped to trial and test the code with their own original Hinode/EIS data. This work was conducted at fortnightly school sessions with the lead author from November 2019 – March 2020, and the students are credited as co-authors of this article.

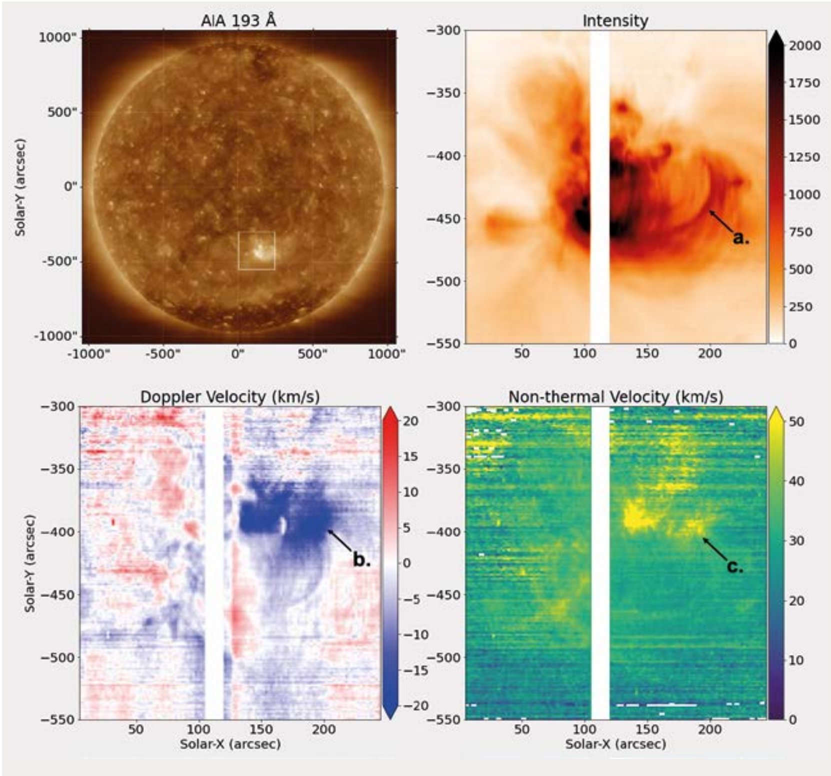
The resources are open access with self-explanatory instructions, and thus suitable for teachers to run as a self-lead activity for A-level students (or equivalent). We encourage readers to promote and connect educators with these resources during school outreach talks, if they consider the topic complementary to their own content (see box "Open source: About the resources").

Solar physics and the A-level curriculum

Multiple topics in the A-level curriculum are directly or indirectly related to the physics of the Sun and solar atmosphere. Stellar evolution and nuclear fusion are often taught in the context of the Sun, but many other topics also apply to processes in the solar atmosphere. Magnetism, for example, is a large part of the A-level curriculum, but rarely in the context of scales larger than the Earth's magnetic field. Magnetism is the main driving force of activity on the Sun's surface, and a direct comparison can be made between coronal loops above a simple active region and the iron filing experiments shown in schools. In both cases, magnetic material (coronal plasma, iron filings) trace lines of force, or magnetic field lines. Additionally, the electromagnetic spectrum and multi-wavelength properties of light are included in the school curriculum, which can be demonstrated by the dramatic differences in active-region appearance as observed across the electromagnetic spectrum.

In our outreach project, we focus on coronal spectroscopy. Atomic physics and spectroscopy are also introduced at A-level, as students learn about the emission of photons at specific spectral lines, caused by transitioning electrons between discrete energy levels of atoms in hot gases. They learn how emission and absorption-line spectra are specific to individual elements and can be used to identify the composition of stars. The study of extreme-ultraviolet (EUV) spectral lines in the solar atmosphere is a direct application of this, as used by imaging spectrometers such as the EUV Imaging Spectrometer (EIS; Culhane *et al.* 2007) onboard the Japanese Hinode satellite launched in 2006.

Spectral lines observed by EIS display Doppler effects, due to plasma motion in the line-of-sight. The Doppler effect is introduced at A-level, usually in the context of soundwaves in day-to-day experiences (e.g. a passing ambulance), and the redshift of distant galaxies. The EIS data analysis resources described below provide students with the opportunity to apply A-level physics knowledge to real research applications, even if they haven't formally covered the entire curriculum at the time of engagement.



1 *Top left: AIA 193 Å image showing the field of view. The other panels show the intensity, Doppler velocity and non-thermal velocity results derived by the students from the Fe XII 195.12 Å Hinode/EIS observations of 12 March 2020, 00:36 UT. (a) Plasma loop shaped by magnetism. (b) Region of strong upflowing plasma. (c) High non-thermal velocities at base of loop.*

Hinode/EIS

EIS observes spectral emission lines from multiple Fe, Si, Ca etc isotopes in the optically thin corona, sensitive to a range in temperatures from 50000 K to over 15 MK. By fitting a single Gaussian curve to the emission spectra of certain lines, we can extract information from the intensity, Doppler velocity and non-thermal velocity of the emitting plasma. Each Gaussian curved is defined by a height, width and centroid wavelength. Some more complex emission spectra require multiple Gaussian fits.

The properties of intensity, Doppler velocity and non-thermal velocity are calculated for each pixel, to produce a map over the EIS field of view. Intensity is determined by the total area under the Gaussian curve, representative of the total emission of the line. Doppler velocity is calculated by the shift in centroid wavelength from a relative "rest" wavelength. This provides the bulk

the Sun

velocity of plasma along the line-of-sight. Non-thermal velocity is related to the width of the Gaussian, and slightly harder to picture conceptually.

Spectral emission lines are not infinitely thin, as multiple processes act to broaden the line and produce a wider Gaussian profile. An example of this in the corona is from plasma motion with no preferential direction, which acts to broaden the line as we observe both red- and blue-shifted plasma equally along the line-of-sight. Thermal processes can cause such plasma motion, and thus hotter plasma will produce broader lines resulting from a higher thermal velocity. Other broadening processes include waves and turbulence, which are incorporated in the "non-thermal velocity". Non-thermal velocity equates to any "excess broadening" after the known broadening processes (e.g. thermal) have been accounted for. These three measurements are simple to compute, yet provide a fundamental insight into plasma processes in the corona. We have produced a user-friendly Python notebook to walk students through the steps of calculating maps of these properties.

The Python notebook

Most scientists use the IDL programming language when working with EIS data, but IDL is not open source. Python, however, is open source, with a wide range of prebuilt functions available in packages such as AstroPy (Astropy Collaboration *et al.* 2018) and SunPy (SunPy Community *et al.* 2020). The use of notebook-style Python code is also beneficial as it provides a logical step-by-step journey through the code. Google Colaboratory, a Google equivalent to popular notebook sites such as Jupyter, does not even require a local Python installation and can be used instantly with an internet connection. This is ideal for working with schools, as no additional preparation time is needed to configure a Python installation on each computer. It also allows students to transition between different devices. Google Colaboratory can be run directly from Google Drive, where students can copy across the open access resources to their private drive to run. Some schools have access to a Google Classroom account, which is essentially a centralized Google Drive platform, managed by teachers with additional safeguarding protection.

The Python notebook takes an input of a pre-provided EIS file (prepared using the SolarSoft eis_prep routine in IDL), and walks the students through the stages of picking a spectral line, producing a fit template and fitting Gaussian curves to each pixel. From here, maps of intensity, Doppler velocity and non-thermal velocity are created by the user. Steps to produce context images from the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA) instrument, to compare to the EIS observations, are also included.

Observations

Active regions are the most dynamic regions of the Sun's atmosphere. Dominated by concentrated and complex magnetic fields, they are the primary source of solar flares and coronal mass ejections. Due to their complexity, EIS observes a significant variation of intensity, Doppler velocity and non-thermal velocity across active regions (compared with the more-uniform quiet Sun), making them an interesting object of study for students. Active region behaviour is also a dominant cause of space weather, an increasingly popular topic for school and public science outreach. To introduce the students to EIS data analysis, we started by looking at EIS observations of an active region from 17 October 2007. By following the analysis steps in the Python notebook, the students produced maps of intensity, Doppler velocity and non-thermal velocity of multiple emission lines, similar to the intensity and velocity maps presented in Baker *et al.* (2012).

In January 2020, the students contributed towards submitting an EIS observing plan, to collect original data of a new active region to study. Despite low solar activity during the observing window, the observing run was a success, and Hinode/EIS took measurements of an unnamed active region on 12 March 2020. We had planned to supervise the students through the analysis of their new data within the guided school sessions. However, due to school closures as a result of Covid-19, the students worked unsupervised from home.

Figure 1 contains a sample of this work, showing EIS maps of the Fe XII 195.12 Å emission line. An image from the SDO is provided for context, showing the EIS field of view. The high-intensity active-region loops are visible, which produce red- and blue-shifted plasma as material flows along the field lines. High non-thermal velocities are observed at the base of the loops. Unfortunately, due to instrumental effects, there is a strip of missing pixels through the centre of the data.

Now in the final year of their A-levels, some of the students are considering studying science or engineering at university. Participating in this project has provided them with the unique and memorable experience of collecting fresh spacecraft data and analysing previously unstudied observations of a solar active region. One student said that the sessions "opened up a new world of knowledge and possibilities of what can be studied" and "provided a more detailed outlook into what university research can progress to". Hopefully, the skills developed during this project will be valuable during university applications and beyond.

Finally, the students also aided in amending and bug-fixing the Python notebook, by reporting errors and pointing out areas where instructions required more detail. As a result, we believe that these resources are now suitable to be used by teachers as an independently run stand-alone extended activity in the classroom. ●

Open source About the resources

The sessions at St Wilfrid's Catholic School were funded by Widening Participation at University College London, as a part of the ORBYTS (Original Research By Young Twinkle Scientists) project (Sousa-Silva *et al.* 2017). The ORBYTS programme partners active scientists with schools to facilitate school involvement in space research. It was originally created to engage pupils in exoplanet research related to the Twinkle mission, but now includes research areas in solar physics, astrophysics and planetary science. As the new solar cycle continues to ramp up in activity, we believe that these resources will provide a unique opportunity to enthuse and inspire the next generation of space scientists, connecting their day-to-day A-level physics to cutting-edge solar physics research. The resources will enable them to be active in the development of the solar physics field, while still in school.

The resources used for this work are open source and can be found at the link below. We believe it is appropriate to promote the resources as a self-contained activity, perhaps to accompany a solar physics outreach talk or similar. They include:

- Introductory PowerPoint covering general topics in solar physics for teachers.
- Introduction to Python exercise notebook, themed around solar physics.
- EIS data analysis folder, including the main Python notebook and data inputs.
- Comprehensive user guide for the analysis code, to explain the background in more detail and provide step-by-step instructions through the notebook steps.

Any questions regarding the use of the resources can be directed to Ryan French at ryan.french.14@ucl.ac.uk.

Download from **github.com/MSSLSolar/Solar-Physics-School-Resources**

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