Living with a star: the many faces of the Sun

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Why?

Solar variability drives variability in the near-Earth environment

- Magnetic field evolution drives that variability

Energy release & transport in magnetised plasma

- Unprecedented wavelength coverage and spatial and temporal resolution probes magnetised processes at intrinsic scales

- A laboratory for astrophysics
Solar physics is about:
• Waves
• Instabilities
• Reconnection
• Turbulence & cross-scale coupling...

Parameter regimes can be very different but insight can be gained from the study of similar plasma processes.

Sub-storm onset in the Earth’s magnetosphere (Kalmoni et al., 2018)

Jupiter’s aurora (UV) (Branduardi-Raymont et al., 2008)

Solar flare ribbons observed by the Swedish Solar Telescope.
Properties of the Sun

• A boring(?) middle aged star (4.5 billion years old)
• In the middle of the main sequence (G2V)
• Powered by fusion in the core
• A magnetic star….

Courtesy University of Swinburne
The Sun dominates our environment

• Provides heat and light
• Creates solar wind, which in turn affects the Earth’s environment
  – from beautiful aurora
  – to serious disruption to satellites
• Erupts with violent CMEs and flares
• Space is part of our environment
Visible face of the Sun
The EUV face of the Sun
Sunspots

Images courtesy of the Galileo Project
http://galileo.rice.edu

Images from Professor Owen Gingerich's copy of the first edition of *Istoria e Dimostrazioni*. 
Sunspots: sources of magnetic field
Measuring the magnetic field

Visible light: 1 March 2000

Magnetogram: 1 March 2000
The sunspot cycle

Solar Cycle 25 Forecast Update
- Released December 9th, 2019 -

Solar Cycle 25 will have a peak SSN of 115 (± 10) in July 2025
Solar Cycle 24/25 minimum will occur in April, 2020 (± 6 months)

NOAA/NASA prediction panel 2019
Movie courtesy of David Hathaway
Rise of the Magnetic Field

- Bundles of strong magnetic field rise from the base of the convection zone.
- Causing sunspots at the surface (photosphere)
- Generating magnetic structures in the corona
- These structures are responsible for solar eruptions (flares and CMEs).
Consequences - violating the 2\textsuperscript{nd} law of thermodynamics?

- First clues corona was hot from 1869 eclipse observations (Young & Harkness)
- 1931 Grotrian identified smearing of Fraunhofer lines -> scattering by fast coronal electrons
- Alfvén (1941) – “corona heated to an extremely high temperature”.

Also speculated that magnetic field played a role. . .
Discovering new elements

- 1868 eclipse Janssen noted bright yellow line at 587.49 nm, assumed it was Na
- Later that year Lockyer identified it wasn’t from any known element – called it *Helios*
- Detected in lava from Vesuvius in 1882
X-ray corona – 1968 -1973

Culhane et al., 1969

Solar soft X-ray spectrum

optical flares. However, a very wide range of X-ray enhancements was observed to correspond to sub-flares. The largest of these enhancements was just as significant as those enhancements correlated with importance 2 flares. We would, therefore, conclude that while a large optical flare will be accompanied by a large X-ray enhancement, the enhancement corresponding to importance 1 flares or sub-flares can be just as large.

An importance 1B flare, which occurred on 1967 October 26 was associated with a considerable X-ray enhancement. Counting rate profiles, obtained during this flare, for the 1-3 Å, 3-9 Å and 8-16 Å bands are given in Fig. 7. The time of the 1-3 Å X-ray peak was 06:14 U.T. while 06:16 U.T. The numbers 1 to 8 on the graph indicate at which spectra were obtained.

The forerunner of X-ray astronomy

Figure 2.5  Skylab x-ray photograph of a solar flare; center of flaring region removed (dark disk) because flare brightness oversaturated the photographic plate (courtesy Space Environment Services Center).
The corona in X-rays – 21st century

5 arcminutes (220,000 km on the sun)

Coronal structure in the sun’s polar region

30 arcseconds (22,000 km on the sun)

X-ray bright points seen as concentrations of magnetic loops for the first time

Detailed structure of active-region loops
Solar Forensics

- Breaking up the UV light from the Sun into the light from hundreds of different electron transitions.

- We use EUV spectrometers and filter-imagers

- Each one gives us information about where the light comes from:
  - composition
  - speed
  - temperature
  - density

- Information you need to model the gas and understand its behaviour
10,000 individual components – built and operated by an international consortium led by UCL MSSL
Million K plasma is hard to confine...

- Orientation of comet tails and 27 day recurrence period of aurora gave the first indication of a charged outflow from the Sun.

- Million K corona expands outward to fill the heliosphere
EIS measurements: source of solar wind

Measurements in ionic emission lines give us enormous amounts of information. E.g., Fe$^{11+}$

Images from Hinode XRT & EIS

Reverse EUV Brightness

Doppler Shift

X-ray brightness
Living in the atmosphere of a star

McComas et al.
Discovery of a Solar Flare: the beginning of space weather

• September 1, 1859

• Independently observed by R. C. Carrington and R. Hodgson

• Magnetic storm commenced early on September

Drawing by Carrington
The above movement was nearly coincidental in time with Carrington’s observation of a bright eruption on the Sun. Discovered over a sunspot. (H.W.N., 2 Dec 1938).
While the contemporary occurrence [of a magnetic storm] may deserve noting, [Mr. Carrington] would not have it supposed that he even leans towards hastily connecting them. “One swallow does not make a summer.”

Energy release in a solar flare

UV, EUV & X-ray wavelengths show us:
- Heated plasma around the current sheet
- The cavity that forms the CME core
- Accelerated particles

Long et al., 2018
Current sheet structure?

- Current sheets in the corona virtually impossible to observe, but can observe:
  - heating
  - line broadening
  - turbulence
  - plasma instabilities
  - faster reconnection

Warren et al. (2018)

Daughton et al. (2009), PIC

Long et al., 2018
Unresolved magnetic structure is capable of destroying polarisation to levels observed.

Consistent with current theory and models of current-sheet instabilities.
Energetic Particles

- **From space:**
  - EUV (Solar Dynamics Observatory)
  - hard X-ray (RHESSI)
- **From the ground:**
  - Radio
    - Extended Owens Valley Radio Array (EOVSA)

Gary et al., 2018
Evolving maps of the coronal magnetic field

- Evolution of the coronal magnetic field over 4 minutes.
- Each frame is separated by 4 seconds.

Fleishman et al., 2020
‘Standard’ Eruptive Model

Shibata et al 1995

Janvier et al 2014
What’s next?

- **Daniel K Inouye Solar Telescope**
- 4m off-axis
  - coronal magnetic fields
  - 16 km diffraction limited resolution (600nm)
- UK development of 4kx4k CMOS cameras (QUB, Andor Technology, UCL-MSSL)
- Science first light last week!

Credit: NSF Daniel K Inouye Solar Telescope
Science Objectives

How does the Sun create and control the Heliosphere – and why does solar activity change with time?

1. What drives the solar wind and where does the coronal magnetic field originate?
2. How do solar transients drive heliospheric variability?
3. How do solar eruptions produce energetic particle radiation that fills the heliosphere?
4. How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Solar Orbiter
Exploring the Sun-Heliosphere Connection

Remote-sensing windows (10 days each)

High-latitude Observations

Mission Summary
Launch: 9 Feb 2020
Cruise Phase: 2.8 / 1.8 years
Nominal Mission: 4 years
Extended Mission: 3.5 years
Orbit: 0.28–0.91 AU (P=150-180 days)
Out-of-Ecliptic View:
Multiple gravity assists with Venus to increase inclination out of the ecliptic to >24° (nominal mission), >33° (extended mission)

Reduced relative rotation:
Observations of evolving structures on solar surface & in heliosphere for almost a complete solar rotation
The Solar Wind Analyser (SWA) will measure:
- Electrons
- Protons
- Heavy ions
in the solar wind at the position of the spacecraft.

SWA consists of three sensors and a common DPU.

Credit: ESA
SWA – Solar Wind Analyser (led by UCL/MSSL)

Electron Analyser System (built at UCL/MSSL)

Proton Alpha Sensor

Heavy Ion Sensor
EUI - EUV Imager (co-led by UCL-MSSL)
What EUI will see

METIS coronagraph FOV
AIA FOV
SWAP FOV
A view on the poles

jHelioviewer
Even further: Solar C_EUVST

A: Seamlessly observe the chromosphere to the corona simultaneously at the same spatial resolution
B: Resolve and track elemental structures (0.4", 1 sec exposure)
C: Measure dynamics of elementary processes (Velocity, density, temperature, composition, ionization)

JAXA led mission – building on Hinotori, Yohkoh & Hinode - Launch 2026

7x higher spatial resolution than Hinode
European Solar Telescope (EST)

- 4m on-axis, polarimetrically compensated
  - Multi-height chromospheric magnetic field - highest sensitivity ever achieved
- Multi-height imaging & spectroscopy at scales where MHD breaks down
- Multi Conjugate Adaptive Optics system similar complexity to ELT
- Daytime AO correction and optical comms similar challenges
  - ground to satellite and point-to-point for communications infrastructures
- First light ~2027/28

Brannon et al., 2015
Solar Physics: the original multi-messenger astronomy

- From space:
  - ‘see’ from gamma-rays to the optical – imaging, spectroscopy and spectropolarimetry
- From the ground
  - optical to radio imaging, spectroscopy and spectropolarimetry
- New instrumentation – Inouye Solar Telescope and Solar Orbiter, Solar C EUVSY, EST (fingers crossed)
- Co-ordination – SOHO and Hinode have pioneered the way

Fundamental Physical Processes
- Waves
- Instabilities
- Reconnection
- Turbulence
- & cross-scale coupling...

Internal dissipation in blazar jets

Thank you!

And don’t miss the Solar Orbiter launch on Monday morning!