Energetic particles and X-rays with EPD and STIX on Solar Orbiter

Sophie Musset
ESA/ESTEC
Solar Orbiter scientific objectives

How does the Sun create and control the heliosphere, and why does solar activity change with time?

- What drives the solar wind and where the coronal magnetic field originate from?
- How do solar transients drive heliospheric variability?
- How do solar eruption produce energetic particle radiation that fills the heliosphere?
- How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Müller. et al (2020)
Solar Orbiter scientific objectives

How does the Sun create and control the heliosphere, and why does solar activity change with time? (Müller et al. 2020)

- What drives the solar wind and where the coronal magnetic field originate from?
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How do solar eruptions produce energetic particle radiation that fills the heliosphere?

• How and where are energetic particles accelerated at the Sun?

How are energetic particles released from their sources and distributed in space and time?

• What are the seed populations for energetic particles?

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From NASA’s Solar Sentinels STDT report
Müller. et al (2020)

Adapted from Krucker et al (2011)
How do solar eruptions produce energetic particle radiation that fills the heliosphere?

JOINING THE DOTS

Solar Orbiter traced an energetic particle event on 21 March 2022 from the Sun through the solar wind.

Particles spiraling out on Sun’s magnetic field lines reach Solar Orbiter.

STIX observes source X-ray flare (red dot), EUI a shock wave (green).

EUI: Extreme Ultraviolet Imager
EPD: Energetic Particle Detector
RPW: Radio and Plasma Waves
STIX: X-ray Spectrometer/Telescope

RPW detects radio signals of accelerated particles and plasma oscillations.

EPD detects particles with various composition and energy.

ESA & NASA/Solar Orbiter/EPD, EUI, RPW & STIX Teams.
Payload

6 remote-sensing instruments
- EUI: Extreme Ultraviolet Imager
- Metis: Coronagraph
- PHI: Polarimetric and Helioseismic Imager
- SoloHI: Heliospheric Imager
- SPICE: Spectral Imaging of the Coronal Environment
- STIX: X-ray Spectrometer/Telescope

4 in-situ instruments
- EPD: Energetic Particle Detector
- MAG: Magnetometer
- RPW: Radio and Plasma Waves
- SWA: Solar Wind Analyser

Müller et al (2020)
Payload

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  - MAG: Magnetometer
  - RPW: Radio and Plasma Waves
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Müller et al (2020)
EPD: Energetic Particle Detector

Rodriguez-Pacheco et al. (2020)

Need to measure energetic particles in-situ with:
• Broad range of energies and composition
• High time resolution
• Directional information

And...
• Get close to the Sun
• Complementary in-situ measurements (magnetic field, plasma parameters...)

⇒ The EPD suite of instruments
EPD: Energetic Particle Detector

Rodriguez-Pacheco et al. (2020)

**EPT/HET**: Electron Proton Telescope/High Energy Telescope (25 keV to hundreds of MeV)

Energetic electrons and protons (EPT/HET)

Heavy ions (HET)

**STEP**: SupraThermal Electrons and Protons (2-80 keV)

**SIS**: Suprathermal Ion Spectrograph (14 keV/n-20.5 MeV/n)

He-Fe between energies just above the solar wind to multi MeV/n energies

Protons and electrons at supra-thermal energies
Energy coverage of EPD for different species
EPD: Energetic Particle Detector

Rodriguez-Pacheco et al. (2020)

Field of view for the different EPD sensors

→ Directional information
EPD: Energetic Particle Detector

Ions: 124–218 keV
Electrons: 54–101 keV

Wimmer-Schweingruber et al. (2021)
EPD: Energetic Particle Detector

Spectrogram

Sected intensity time profiles

Pitch angle coverage

Wimmer-Schweingruber et al. (2021)
EPD: Energetic Particle Detector

Fluence for selected species in the 21 July 2020 event

Mass histogram

Mason et al. (2021)
EPD: Energetic Particle Detector

Calibrated data = L2 data sets

- On SOAR
- Also at https://espada.uah.es/epd/data/archive with preview plots
- Quicklook summary plots available at https://espada.uah.es/epd/data/plots/quicklook
- AMDA, propagation tool…

→ Read documentation for caveats in the data
→ Ask the instrument team!

Level 3 data (e.g. pitch angle distribution) will be distributed as well in the future
EPD: Energetic Particle Detector

Combined dynamic spectra for energetic ions and electrons as measured by STEP, EPT and HET in the sunward looking direction (along the average Parker spiral)
EPD: Energetic Particle Detector

Time series for energetic ion and electron intensities for selected particle energies. EPT and HET omnidirectional intensities are calculated by averaging the measurements of the four telescopes.
Dynamic spectra for energetic electrons observed by all EPT telescopes.
EPT sun and anti-sun telescopes look along the average Parker spiral in opposite directions.
EPT north and south telescopes point respectively towards the north and south ecliptic hemispheres.
Dynamic spectra for selected ion species as measured by the SIS A telescope (looks sunward in the direction of the average Parker spiral)
STIX: X-ray Spectrometer/Telescope

Krucker et al. (2020)

PI: Samuel Krucker, FHNW

- Spectroscopy of X-ray emission in 4-150 keV energy range
- Indirect imaging (Fourier-based)

Distribution in space, time and energy of X-ray emitting energetic electrons in the solar atmosphere

Flare position, lightcurves and spectrum in X-ray, on June 7 2020.
STIX: Spectrometer/Telescope Imaging X-rays

Krucker et al. (2020)
STIX: Spectrometer/Telescope Imaging X-rays

Krucker et al. (2020)
STIX: Spectrometer/Telescope Imaging X-rays

What do we see with X-rays?

Bremsstrahlung emission
STIX: Spectrometer/Telescope Imaging X-rays

What do we see with X-rays?

Bremsstrahlung emission

From Klein et al. (accepted)
What do we see with X-rays?

Hot plasma "thermal emission" in loops

Bremsstrahlung emission

From Klein et al. (accepted)
STIX: Spectrometer/Telescope Imaging X-rays

What do we see with X-rays?

- Hot plasma “thermal emission” in loops
- Energetic electrons “non-thermal emission” in footpoints

Bremsstrahlung emission

From Klein et al. (accepted)
STIX: Spectrometer/Telescope Imaging X-rays

Imaging: two grids to create a moiré pattern
STIX: Spectrometer/Telescope Imaging X-rays

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Imaging: two grids to create a moiré pattern

STIX pixels

8.8 mm
STIX: Spectrometer/Telescope Imaging X-rays

Imaging: two grids to create a moiré pattern

- STIX pixels

- Average pitch of the grid
  → One spatial scale (resolution)

- Orientation (average angle) of the grid
  → One direction in space

- One moiré pattern
  = one visibility in the Fourier space
The moiré pattern amplitude and phase depend on the source size and location.

- **Extended source**
- **Off-axis source**
STIX: Spectrometer/Telescope Imaging X-rays

STIX = 30 visibilities

Courtesy of S. Krucker
STIX: Spectrometer/Telescope Imaging X-rays

STIX = 30 visibilities

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STIX: Spectrometer/Telescope Imaging X-rays

STIX = 30 visibilities

Courtesy of S. Krucker
Flare of April 17, 2021

Courtesy of S. Krucker
STIX: Spectrometer/Telescope Imaging X-rays

Imaging algorithms

Backprojection = Fourier transform

Natural weighting

Uniform weighting

Source + instrument response
STIX: Spectrometer/Telescope Imaging X-rays

Imaging algorithms

Backprojection = Fourier transform

CLEAN algorithm

Source + instrument response

Natural weighting

Maximum Entropy Method

Uniform weighting

Expectation Maximization

Visibility Forward Fit
Comparing Solar Orbiter observations with “Earth-based” observatories (e.g. SDO)

→ The challenge of rotation & projection

Massa et al. (in revision)
STIX: Spectrometer/Telescope Imaging X-rays

X-ray spectroscopy with STIX
- 30 energy bins
- Lowest cadence 0.1 sec

Spectral distribution of energetic particles
→ To be compared to spectral distribution of energetic electrons in-situ (EPD)

Battaglia et al. (2021)
STIX: Spectrometer/Telescope Imaging X-rays

STIX flares

STIX microflares during commissioning phase

Battaglia et al. (2021)

264 flares detected by STIX in 2021

STIX flare list:
https://datacenter.stix.i4ds.net/view/flares/list
STIX: Spectrometer/Telescope Imaging X-rays

✓ STIX is observing (almost) all the time since January 2021
Because of low telemetry, not all data is downloaded from the spacecraft.

For interesting time intervals (i.e. during flares), “pixel data” is downloaded: counts in different pixels over time
→ Necessary to reconstruct images
→ Different time binning can be requested
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At other times, “spectrogram data” is downloaded
→ Counts summed over pixels and detectors
→ No imaging
→ Different time binning possible
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YOU can request data for your favorite flare (stored for a few weeks in onboard memory)
STIX: Spectrometer/Telescope Imaging X-rays

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Because of low telemetry, not all data is downloaded from the spacecraft. Low latency data is used to produce quicklooks (~ updated daily):

https://datacenter.stix.i4ds.net/view/plot/lightcurves

Science data include pixel data (L1) and spectrogram data (L4)
You can request data (will give the data set priority to be downloaded)
Request form:
https://datacenter.stix.i4ds.net/view/datareq/form

Ask the team for help analyzing the data set: software and data format still evolving at this point

Data access: the data is publicly accessible (practically) as soon as it is downloaded from the spacecraft (on the STIX data center at the moment)

Authorship policy: no need to include the STIX PI or STIX team. Only include authors who actually contributed to the study.
ESA Science Research Fellowship

• **What?**
  ➤ independent postdoctoral fellowship for ESA State nationals
  ➤ research project covering any topic in space science
  ➤ 2 + 1 years (proposal for 3rd year extension)

• **Where?**
  ➤ ESTEC (Netherlands), ESAC (Spain) or STScI (USA)

• **Why?**
  ➤ **100% research time** (optionally <20% functional work, e.g. archive/data science, citizen science, operations, calibration, communication)
  ➤ insights into ESA environment & activities
  ➤ mentoring from senior ESA Science Faculty members
  ➤ training available (e.g. spacecraft design, soft skills, management)
  ➤ 3000-4200€ net monthly salary (depending on location & experience)
  ➤ comprehensive health coverage

Website: https://www.cosmos.esa.int/web/space-science-faculty/opportunities/research-fellowships  
contact: yannis.zouganelis@esa.int