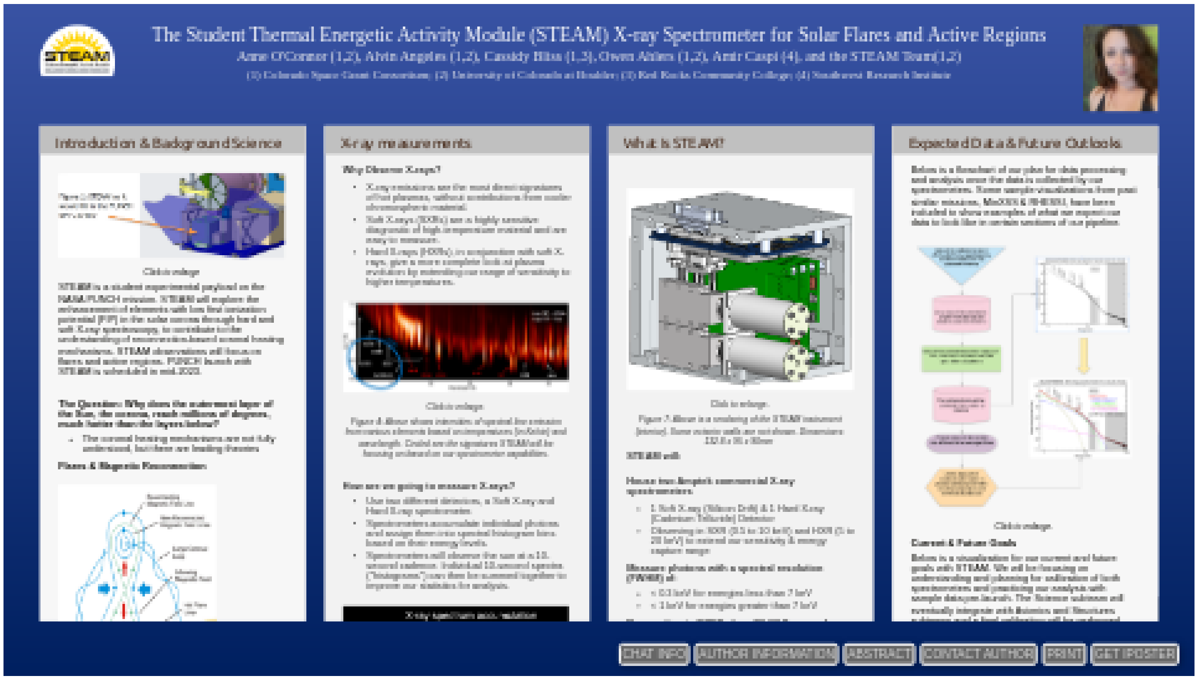
The Student Thermal Energetic Activity Module (STEAM) X-ray Spectrometer for Solar Flares and Active Regions



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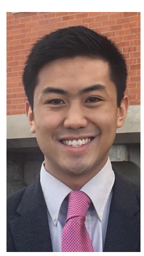
(1) Colorado Space Grant Consortium; (2) University of Colorado at Boulder; (3) Red Rocks Community College; (4) Southwest Research Institute

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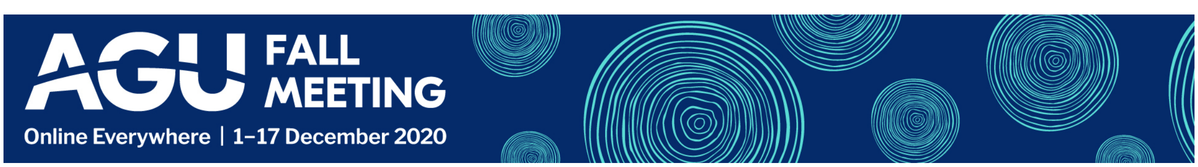
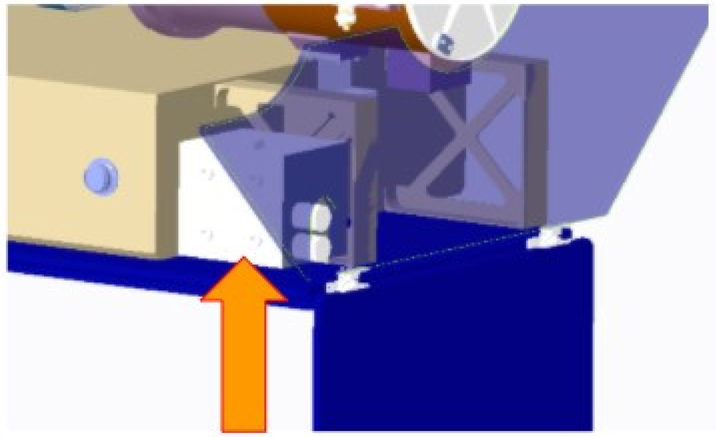


INTRODUCTION & BACKGROUND SCIENCE

Figure 1: STEAM as it would fit in the PUNCH NFI satellite



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STEAM is a student experimental payload on the NASA PUNCH mission. STEAM will explore the enhancement of elements with low first ionization potential (FIP) in the solar corona through hard and soft X-ray spectroscopy, to contribute to the understanding of reconnection-based coronal heating mechanisms. STEAM observations will focus on flares and active regions. PUNCH launch with STEAM is scheduled in mid-2023.

The Question: Why does the outermost layer of the Sun, the corona, reach millions of degrees, much hotter than the layers below?

- The coronal heating mechanisms are not fully understood, but there are leading theories

Flares & Magnetic Reconnection

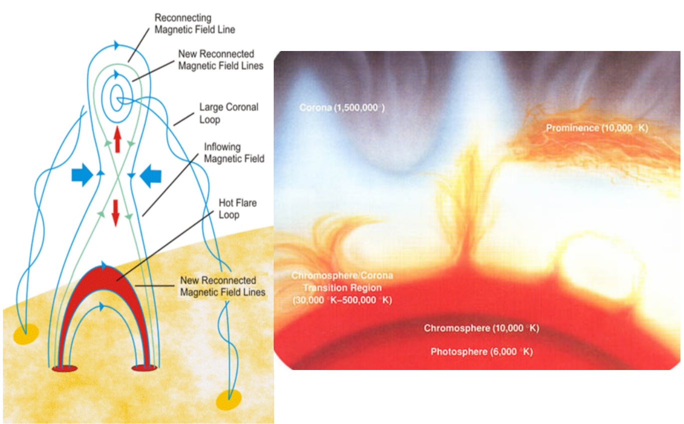

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Figure 2: (Left) Cartoon schematic of magnetic reconnection in a flare. Credit: NASA. (Right) Diagram of outer layers of the Sun, with corresponding temperature. Note high coronal temperatures. Credit: NASA.

A Theory: Coronal plasma is heated through energy release from magnetic reconnection during flares and nanoflares (very small, very frequent flare-like events).

- Magnetic reconnection: oppositely oriented magnetic field lines cancel out and release stored energy
- The reconnection changes the overall magnetic field configuration as the field falls to a lower energy state

- This results in a rapid release of energy in the form of flares and nanoflares

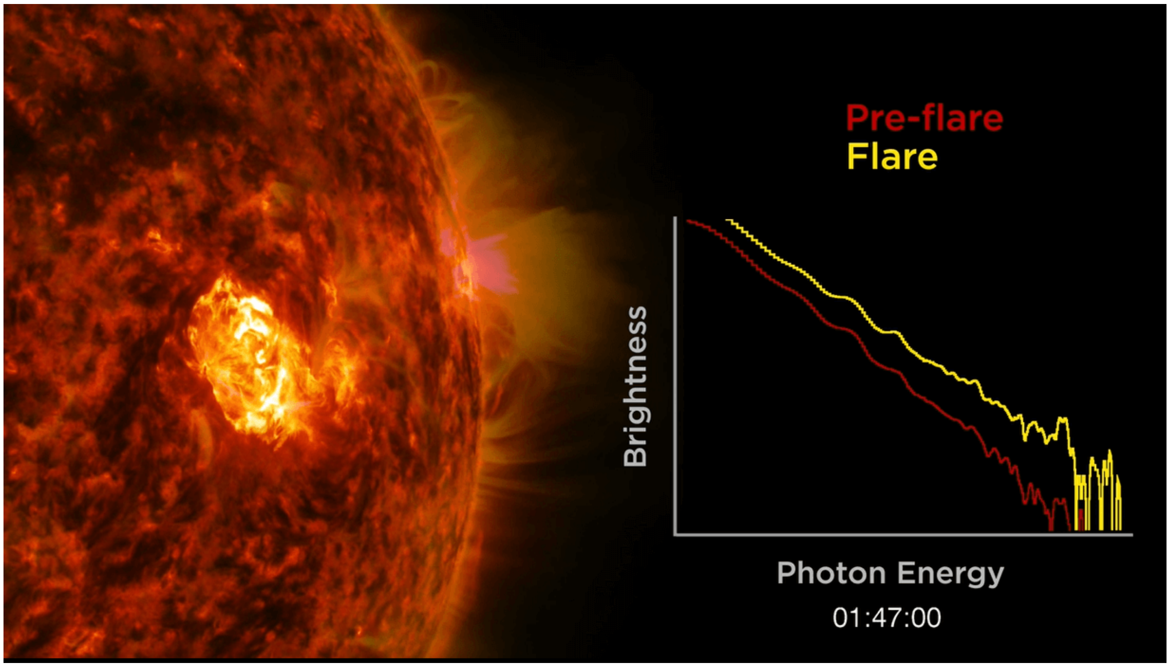

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Figure 3: Snapshot of MinXSS soft X-ray spectra during a solar flare. Credit: MinXSS & NASA.

The Coronal Plasma: STEAM will study X-ray emissions from the hot coronal plasma to search for signatures of magnetic reconnection-based heating by measuring the abundances of key low FIP (first ionization potential) elements

- Emission lines of low FIP (<10 eV) elements (K, Na, Al, Ca, Mg, Fe, Si) are typically prominent above the thermal continuum.
- Their abundances are typically enhanced by a factor of ~4 in the corona over chromospheric abundances
- Abundances allow STEAM to infer the origin of heated plasma for flares and active regions (AR), as the enhancement hints at whether the plasma comes from the corona itself, the chromosphere, or some mixture of origin.

X-RAY MEASUREMENTS

Why Observe X-rays?

- X-ray emissions are the most direct signatures of hot plasmas, without contributions from cooler chromospheric material.
- Soft X-rays (SXRs) are a highly sensitive diagnostic of high-temperature material and are easy to measure.
- Hard X-rays (HXRs), in conjunction with soft X-rays, give a more complete look at plasma evolution by extending our range of sensitivity to higher temperatures.

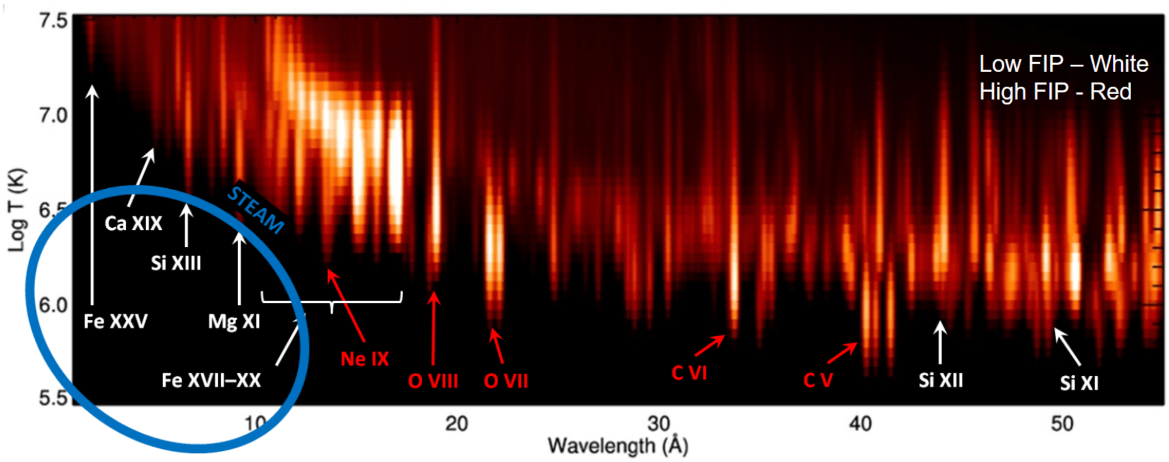

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Figure 4: Above shows intensities of spectral line emission from various elements based on temperatures (in Kelvin) and wavelength. Circled are the signatures STEAM will be focusing on based on our spectrometer capabilities.

How are we going to measure X-rays?

- Use two different detectors, a Soft X-ray and Hard X-ray spectrometer.
- Spectrometers accumulate individual photons and assign them into spectral histogram bins based on their energy levels.
- Spectrometers will observe the sun at a 10-second cadence. Individual 10-second spectra ("histograms") can then be summed together to improve our statistics for analysis.

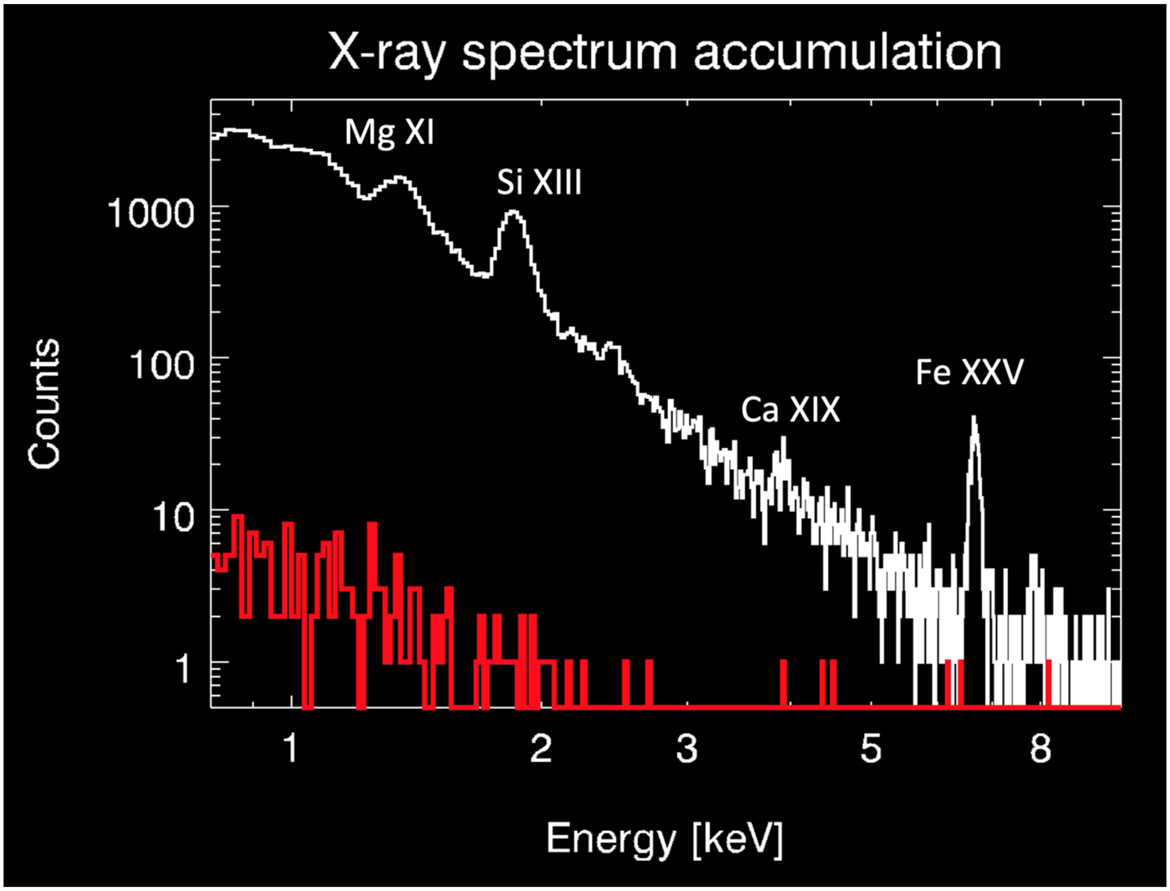

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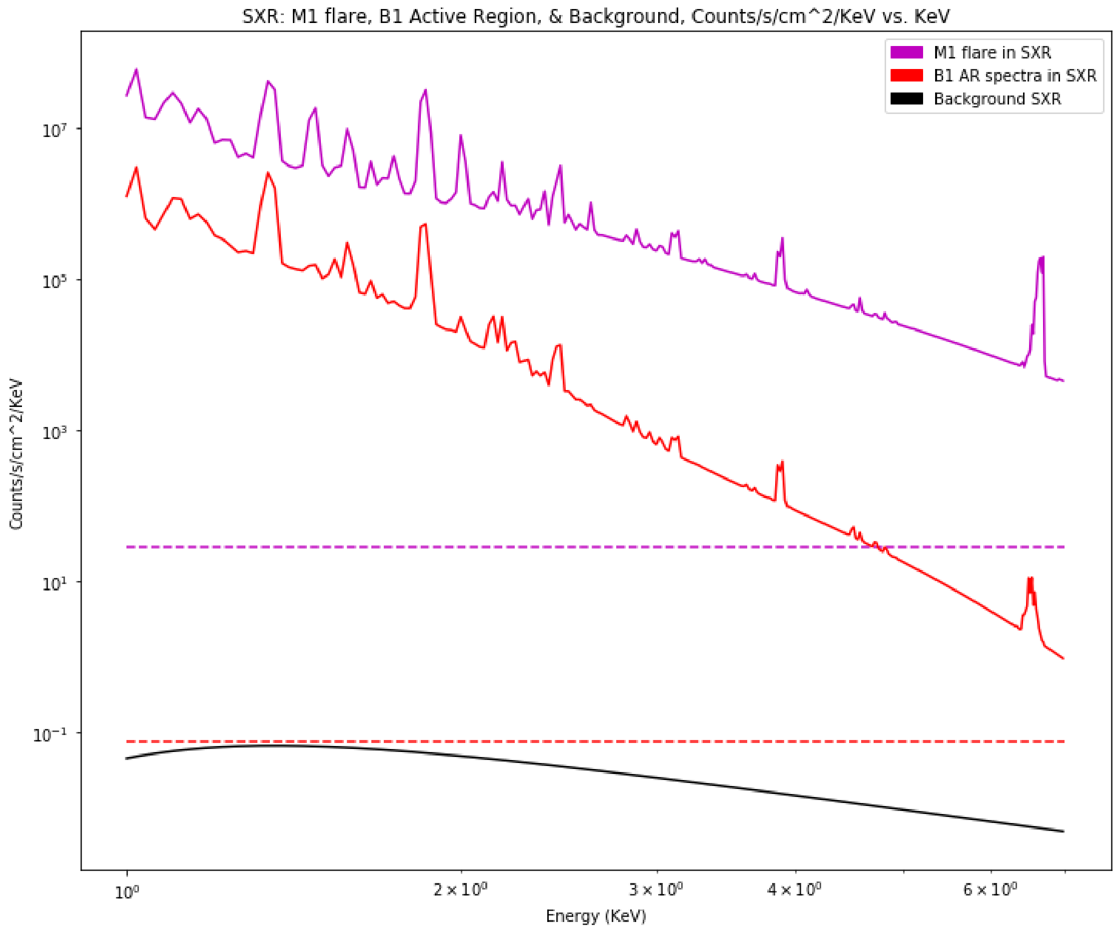
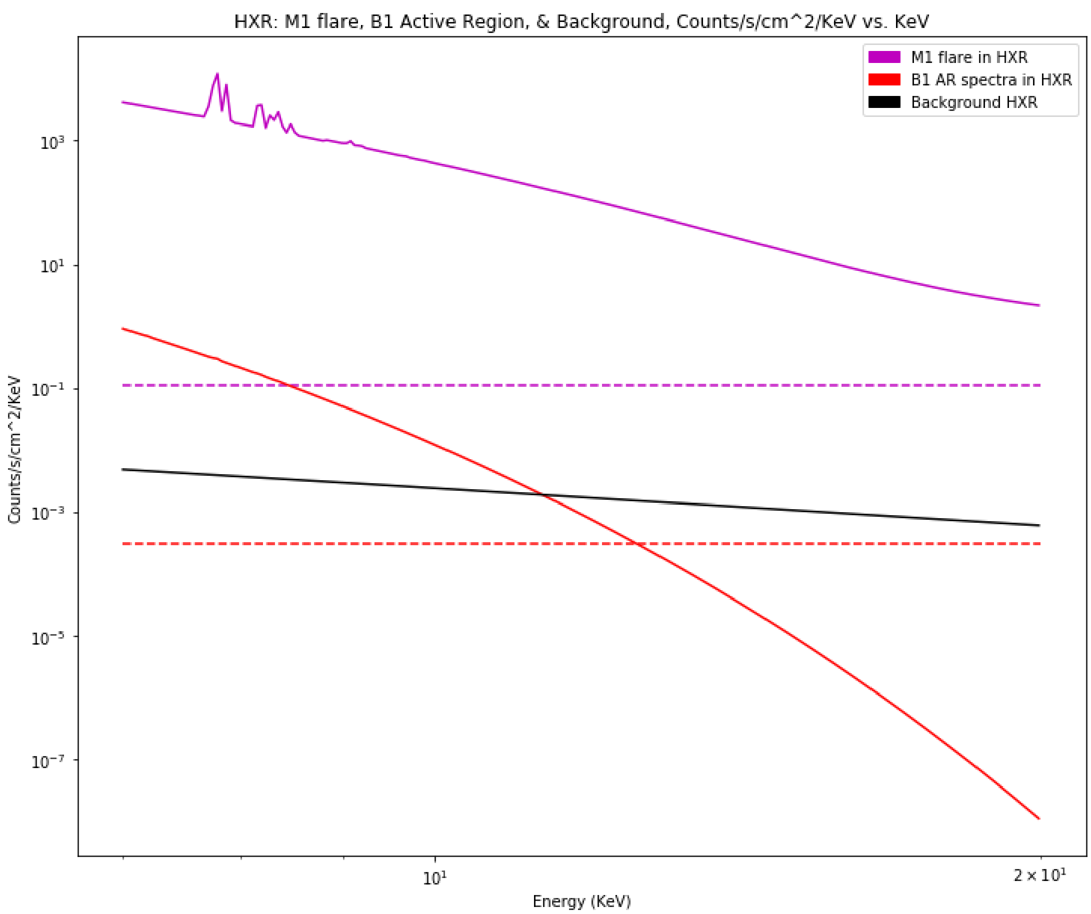
Figure 5: Snapshot of a simulated spectrum accumulation. The lower red line represents a single histogram from a single measurement. The white line represents the total spectrum: multiple red histograms added together.

Field of View & Cosmic Background X-ray Radiation

STEAM has taken into account estimated values for expected cosmic background radiation within our instrument sensitivities and compared against sample Active Region and Flare activity data. It was clear upon our analysis that the background X-ray radiation would not interfere with our scope to within a 10-degree field of view. This has allowed for more flexibility in design collaboration with NIFI.

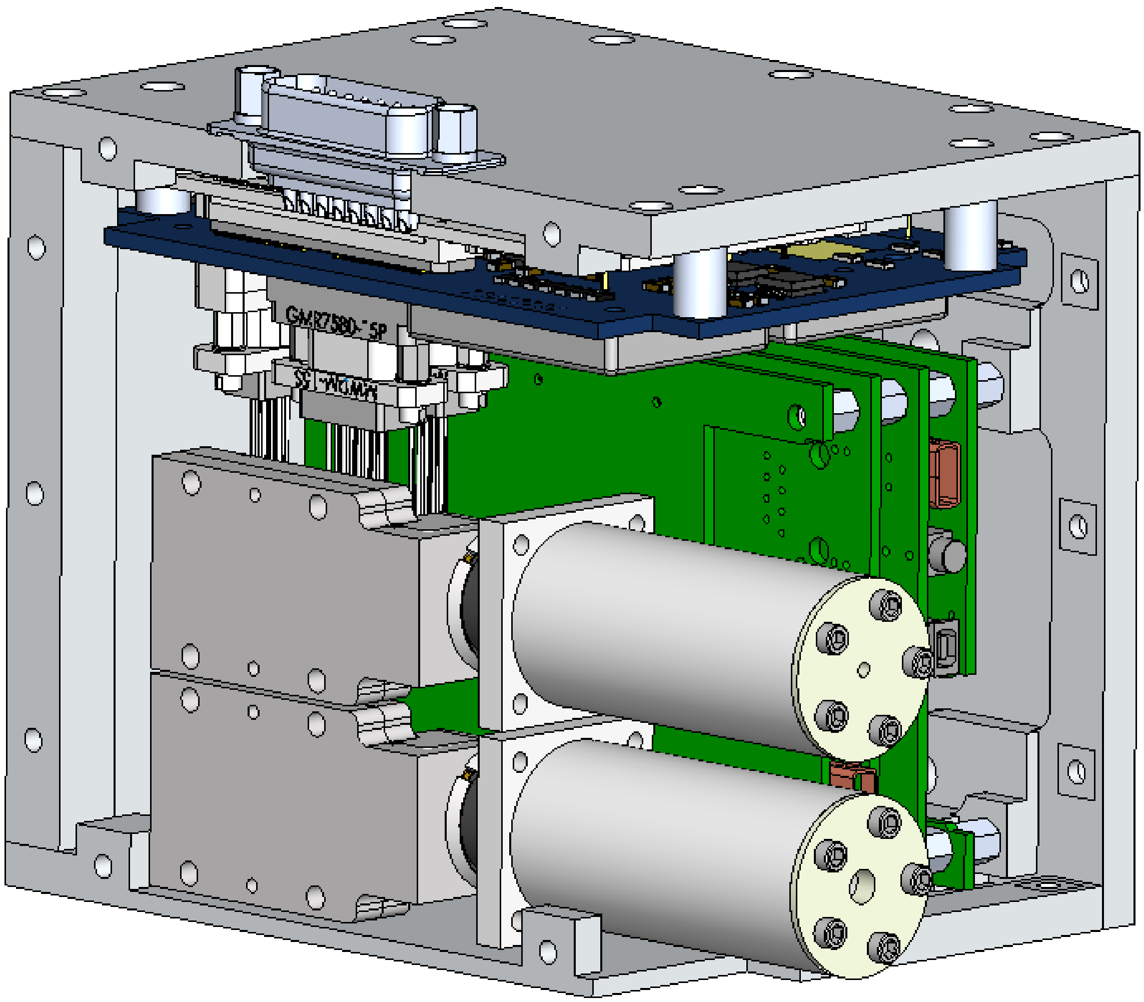

SXR: M1 flare, B1 Active Region, & Background, Counts/s/cm^2/KeV vs. KeV
M1 flare in SXR
B1 AR spectra in SXR
Background SXR
Counts/s/cm^2/KeV
Energy (KeV)


HXR: M1 flare, B1 Active Region, & Background, Counts/s/cm^2/KeV vs. KeV
M1 flare in HXR
B1 AR spectra in HXR
Background HXR
Counts/s/cm^2/KeV
Energy (KeV)

Click to enlarge

Figure 6: Above is a graph of M1 GOES class flare (Purple) and a B1 GOES class active region (red) in soft (top) and hard (bottom) X-rays with Cosmic X-ray Background contribution (Black). The Y-axis is Counts/s/cm^2/KeV and the X-axis is in KeV. The dotted lines represent 1 count over an integration period for their repsective solid colored lines.

WHAT IS STEAM?



Click to enlarge.

Figure 7: Above is a rendering of the STEAM instrument (interior). Some exterior walls are not shown. Dimensions: 132.8 x 95 x 90mm

STEAM will:

House two Amptek commercial X-ray spectrometers

- 1 Soft X-ray (Silicon Drift) & 1 Hard X-ray (Cadmium Telluride) Detector
- Observing in SXR (0.5 to 10 keV) and HXR (5 to 20 keV) to extend our sensitivity & energy capture range

Measure photons with a spectral resolution (FWHM) of:

- < 0.3 keV for energies less than 7 keV
- < 1 keV for energies greater than 7 keV

Be sensitive to GOES class C1-X1 flares and active regions above GOES class A1

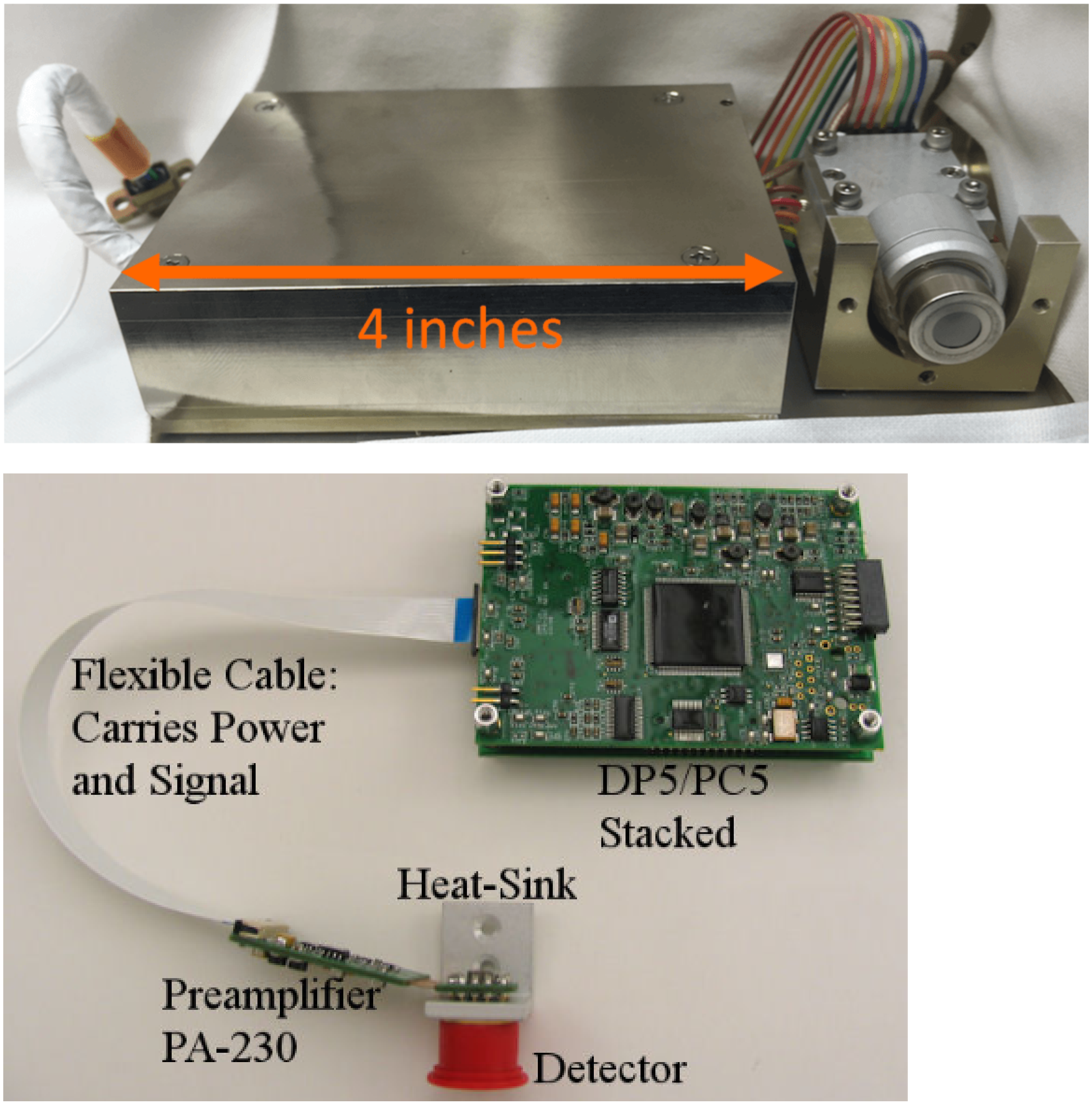
- STEAM will produce spectra every ~1 minute for flares, and at least one every 6 hours for active regions.

Integrate individual X-ray spectra for 10 seconds

- Provides adequate subsamples to mitigate data loss due to interference.

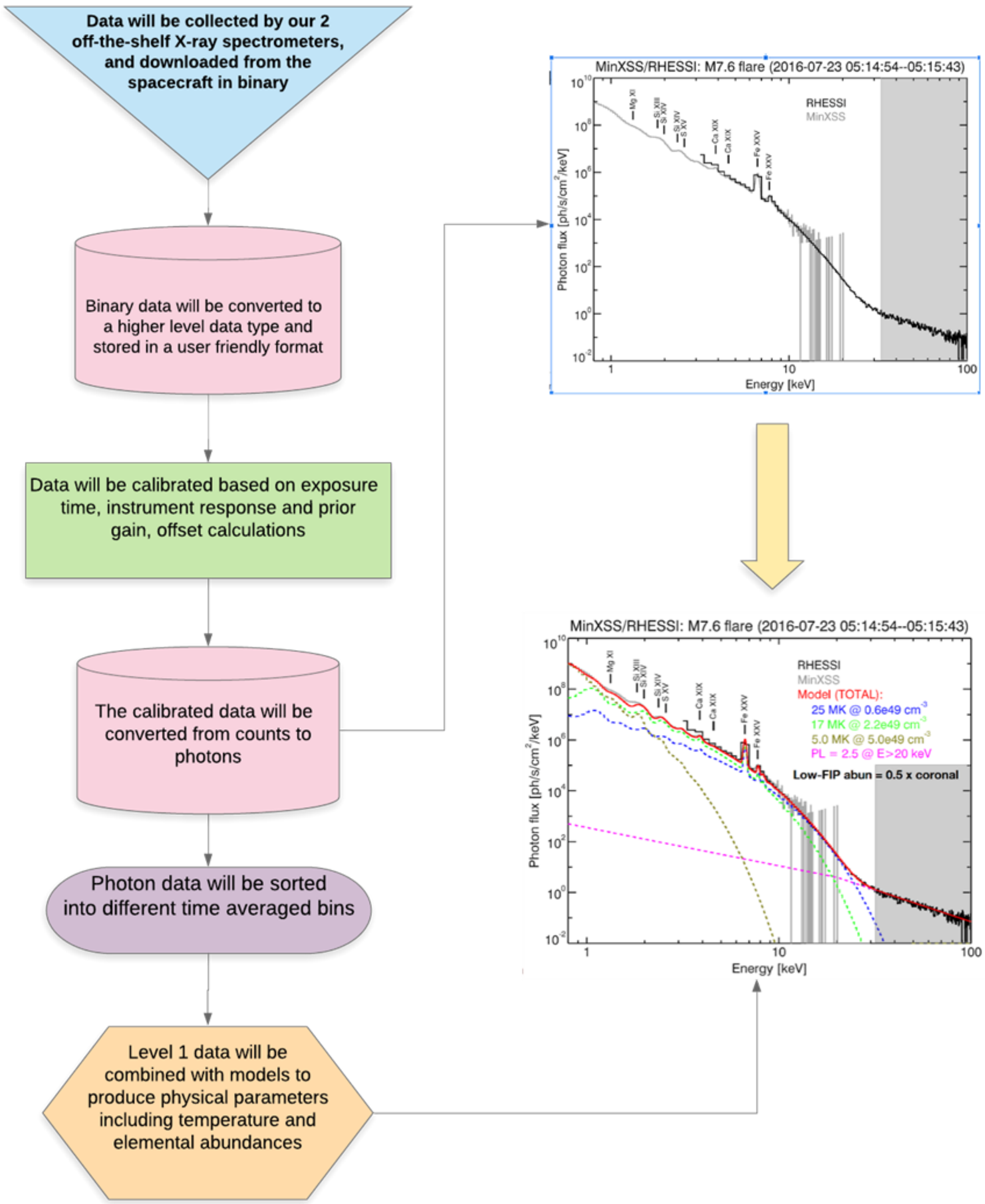
Click to enlarge.

Figure 8: Below is some of the detector's hardware. Top: exterior of spectrometer. Bottom: interior hardware of spectrometer.



EXPECTED DATA & FUTURE OUTLOOKS

Below is a flowchart of our plan for data processing and analysis once the data is collected by our spectrometers. Some sample visualizations from past similar missions, MinXSS & RHESSI, have been included to show examples of what we expect our data to look like in certain sections of our pipeline.



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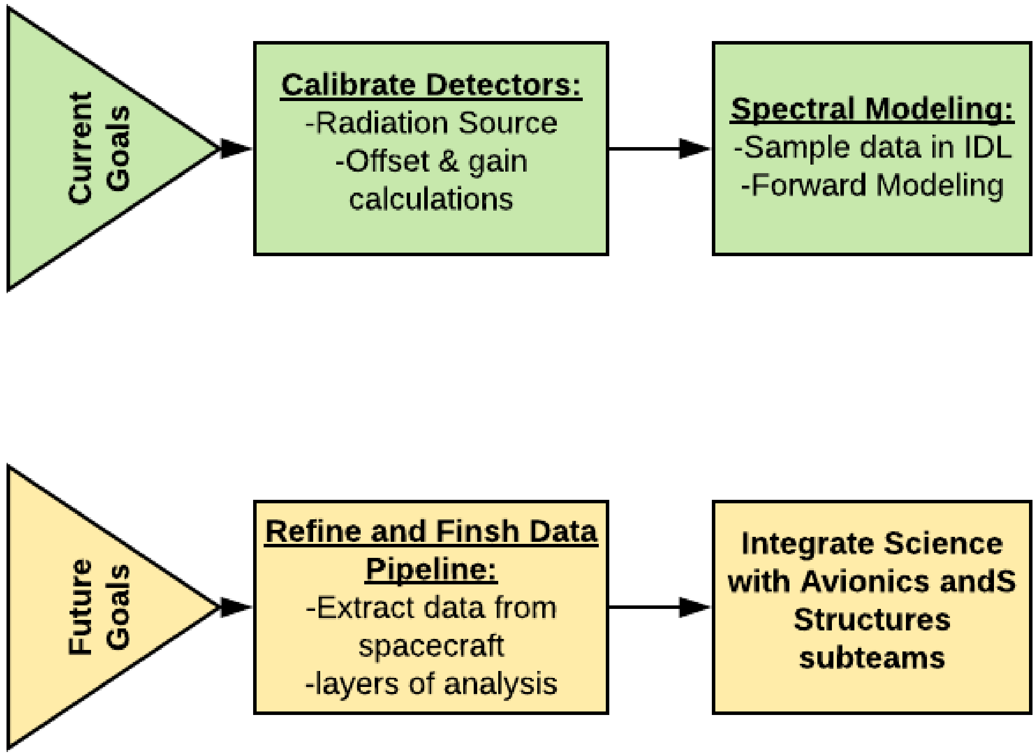
Current & Future Goals

Below is a visualization for our current and future goals with STEAM. We will be focusing on understanding and planning for calibration of both spectrometers and practicing our analysis with sample data pre-launch. The Science subteam will eventually integrate with Avionics and Structures subteams and a final calibration will be performed before launch once STEAM is fully assembled. Once STEAM has launched, we will be ready to collect and analyze data sent from STEAM through the spacecraft.



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ABSTRACT

STEAM will explore how solar coronal plasmas are heated in flares and quiescent active regions by measuring the enhancement of elements with low first ionization potential (FIP) in soft (0.5-10 keV) and hard (5-30 keV) X-rays to distinguish signatures of reconnection-based coronal heating mechanisms. Typically, coronal abundances of low-FIP elements (Mg, Si, Fe, Ca) are enhanced by a factor of ~4 above chromospheric abundances. Measuring the abundances of low-FIP elements for various ions at different temperatures provides insight into the coronal or chromospheric origins of the heated plasma. X-ray emissions, including spectral lines and continuum, provide the most direct signatures of hot coronal plasma. Measuring in both soft and hard X-rays allows STEAM to capture a wider range of emission, extending our sensitivity and thus providing a more complete look at plasma evolution.

STEAM's soft and hard X-ray spectrometers will measure individual incident photons and their energies. Combined, the detectors will cover X-ray emissions from 0.5 to 30 keV, with spectral resolutions of <0.2 and <1 keV FWHM in soft and hard X-rays, respectively. STEAM will generate spectra with a cadence of 10 seconds, and will be optimized to observe flares of GOES class C1-X1 and active regions above GOES class A1. STEAM will utilize forward modeling with bremsstrahlung and atomic emission databases to fit physical parameters such as temperature and elemental abundance to observed spectral data.

STEAM is a student payload hosted on one of the PUNCH Small Explorer spacecraft with an expected launch in mid-2023 and nominal 2-year mission life. STEAM's spectral observations of solar flares and quiescent active regions in soft and hard X-rays during the rise phase of solar cycle 25 will aid in measuring physical parameters to help constrain potential coronal heating mechanisms. We will present the STEAM science motivation, design, current progress, and future outlook.