Soft X-Ray Measurements and Spectrum Analysis

SDO EVE Science Meeting

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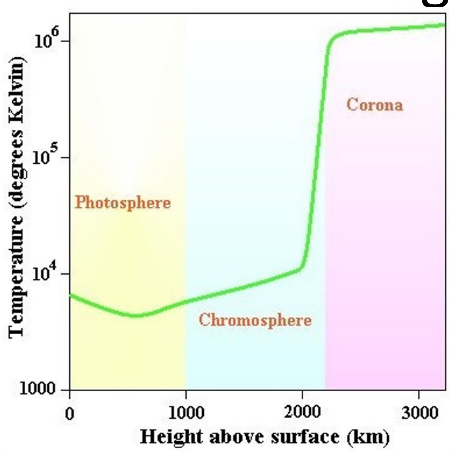
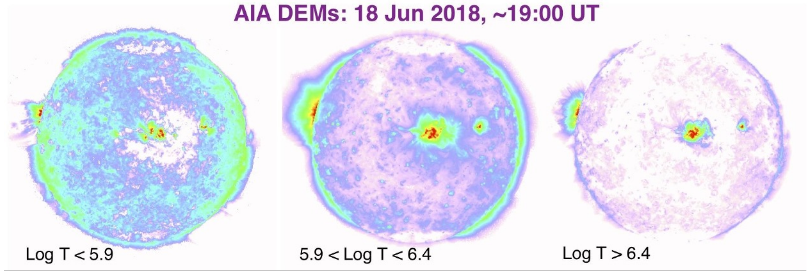
High-Level Motivational Summary

- The sun's corona is orders of magnitude hotter than the photosphere. Why?
- Abundances of elements change during different solar events. Why?
- Soft X-rays (SXR) are always present in the sun, but 100x brighter during flares.
- Emission lines for important elements (Fe, Si, Mg, S, etc.) are in the SXR regime.

Coronal Heating



Active Regions



Solar Flares

The First Ionization Potential (FIP) Factor

- The FIP the amount of energy to remove the first valence electron from a neutral atom
- From Feldman 2003 we can see that a number of elements have an Ionization Potential (I.P.) of 10 or less eV
  - Na, Mg, Al, Si, Ca, Fe, Ni
- S has an I.P. close to 10 eV
- An abundance factor (AF) can be applied to low and mid-FIP elements to be used in modeling (discussed later)

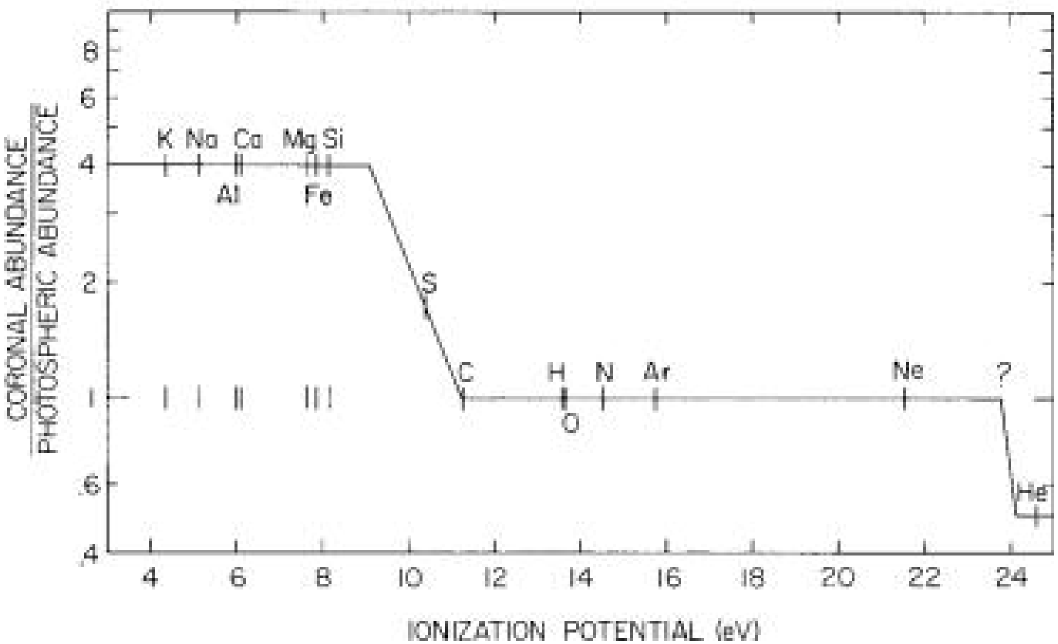
Element		I.P. (eV)	Photospheric abundance		$\log_{10}$ SUA Abundance above typical quiet regions	
			$\log_{10}^{1}$	Relative to Mg	$3\times10^4 \le T_e \le 8\times10^5$ K	$\approx 1.4\times10^6$ K
1	H	13.6	12.00[1]	26300	12.00	12.00
2	He	24.6	10.93[1,2] ±.004	2240	10.93	10.93
6	C	11.3	8.52[1] ±.06	8.7	8.52	8.52
7	N	14.5	7.92[1] ±.06	2.2	7.92	7.92
8	O	13.6	8.83[1] ±.06	18	8.83	8.83
10	Ne	21.6	8.11[2] ±.06	3.4	8.11	8.11
11	Na	5.1	6.32[1] ±.02	0.056	6.62	6.92
12	Mg	7.6	7.58[1] ±.01	1.0	7.88	8.18
13	Al	6.0	6.49[1] ±.01	0.081	6.79	7.09
14	Si	8.2	7.56[1] ±.01	0.96	7.86	8.16
16	S	10.4	7.33[1] ±.06	0.56	7.33	7.33
18	Ar	15.8	6.59[2] ±.06	0.12	6.59	6.59
20	Ca	6.1	6.35[1] ±.01	0.059	6.65	6.95
26	Fe	7.9	7.50[1] ±.01	0.83	7.80	8.10
28	Ni	7.6	6.25[1] ±.01	0.047	6.55	6.85

Feldman, U., and K. G. Widing. "Elemental abundances in the solar upper atmosphere derived by spectroscopic means." *Space Science Reviews* 107.3-4 (2003): 665-720.

How FIP Effects Abundances in the Corona vs Photosphere

- Low-FIP elements have an I.P. of less than about 10 eV
  - These elements are about 4x more abundant in the corona as in the photosphere
- S is considered mid-FIP
  - This element is about 2x as abundant as photospheric
- High-FIP elements are those such as O, Ne, and He
  - These elements have similar abundances as photospheric, possibly even depleted
- These values are for quiet sun

Coronal vs. Photospheric Relative Abund.



Feldman, U., and K. G. Widing. "Elemental abundances in the solar upper atmosphere derived by spectroscopic means." *Space Science Reviews* 107.3-4 (2003): 665-720.

Key Science Question

- Which heating mechanisms are dominant in making the solar corona more than 100 times hotter than the photosphere?
  - There are a few main theories that likely all play a part in coronal heating. During quiescent times, elemental abundances should remain near chromospheric abundances (ex. Feldman values).
  - During flaring times a change in these elemental abundances could support one method of coronal heating.

The coronal abundances during quiescent times are supported for Mg, Si, S, and Fe

Launch of a Sounding Rocket on June 18, 2018

- Launched out of White Sands Missile Range – New Mexico
- This flight was an under-flight calibration for SDO EVE
- Nineteen Sensors were flown
    - One of which was DAXSS!

One of the Instruments Flown Was the New Rocket X123

- The Amptek X123 FAST-SDD is a fast counting silicon drift detector
- Measures the counts of incident photons and sorts into a histogram of their energies
- Better spectral resolution and higher counting rate than previous model
    - 0.079 eV FWHM at 1 keV compared to 0.150 eV FWHM on the MinXSS-1 CubeSat

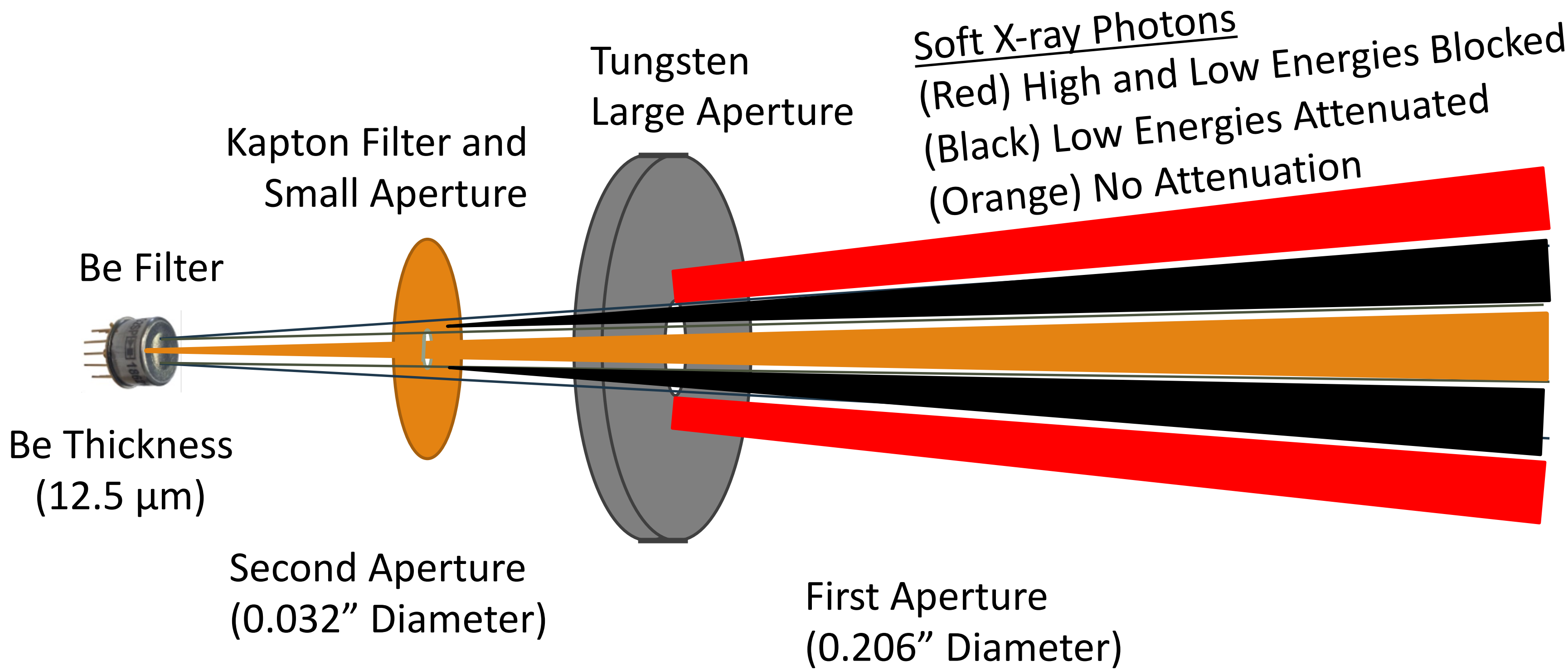
X123 Electronics

X123 Sensor Head

FAST-SDD with Be Window

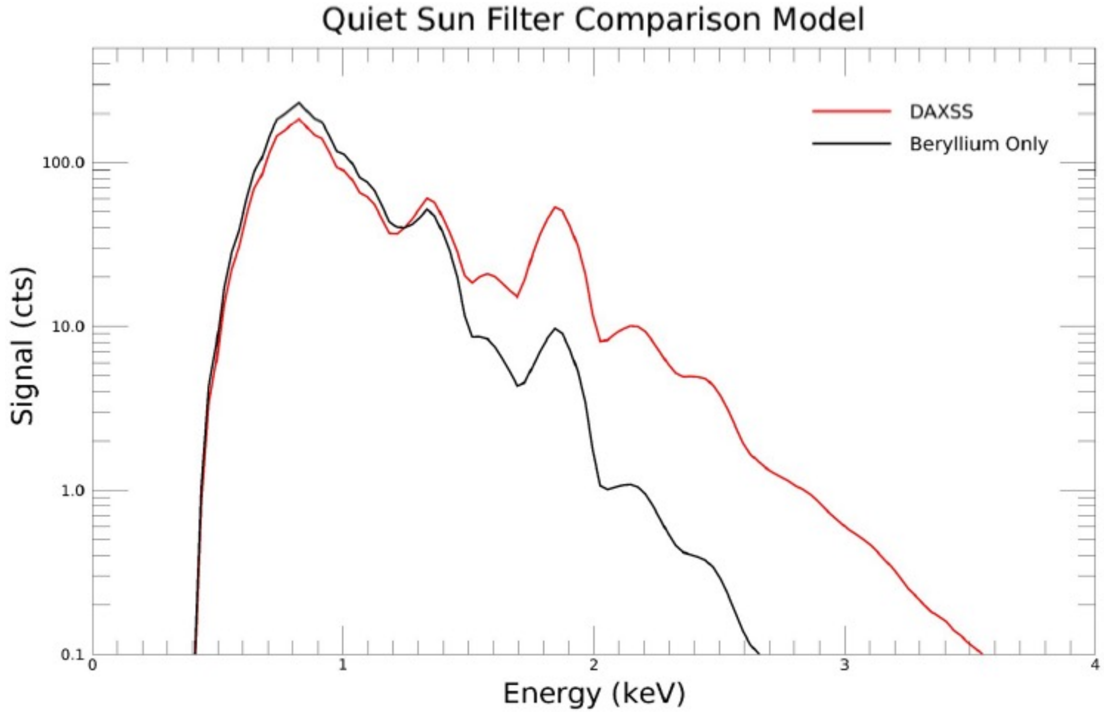
Novel Dual Aperture Provides Wider Energy Coverage Without Saturating the Instrument

- Dual Aperture X-ray Solar Spectrometer (DAXSS)



These Two Improvements Provide a Much Better Spectral Response

- Dual Aperture X-ray Solar Spectrometer (DAXSS) allowed more transmission of higher energy photons without saturating the lower energy counts



Credit: Robert Sewell

Previous Rocket Spectrum - Fewer Emission Lines and Wider Energy Bins

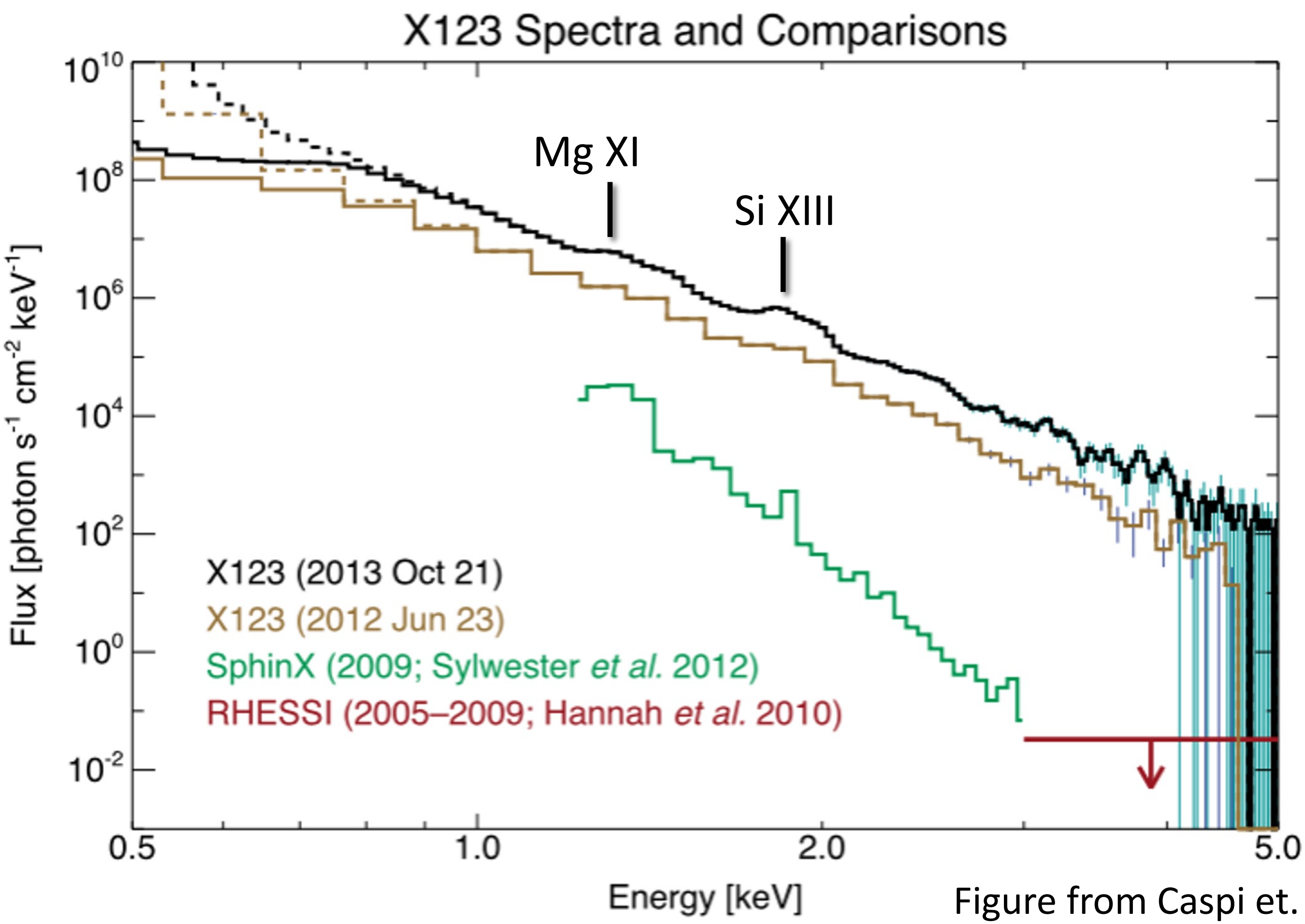
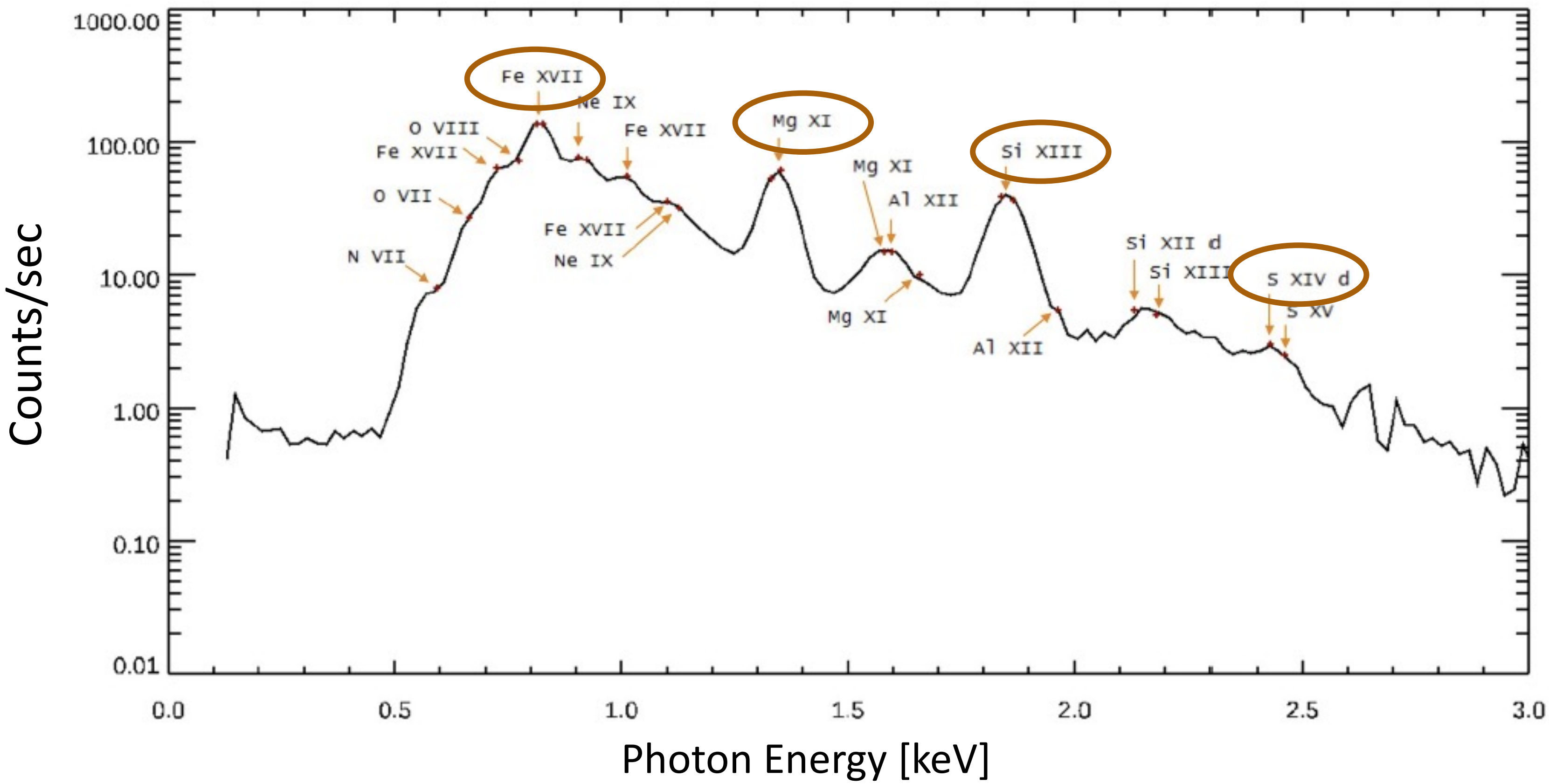


Figure from Caspi et. al., Ap. J., 2015

Recent Rocket Spectrum - Emission Lines Are More Identifiable and Better Resolved

- Now we can clearly identify emission lines from Fe, Mg, Si, S



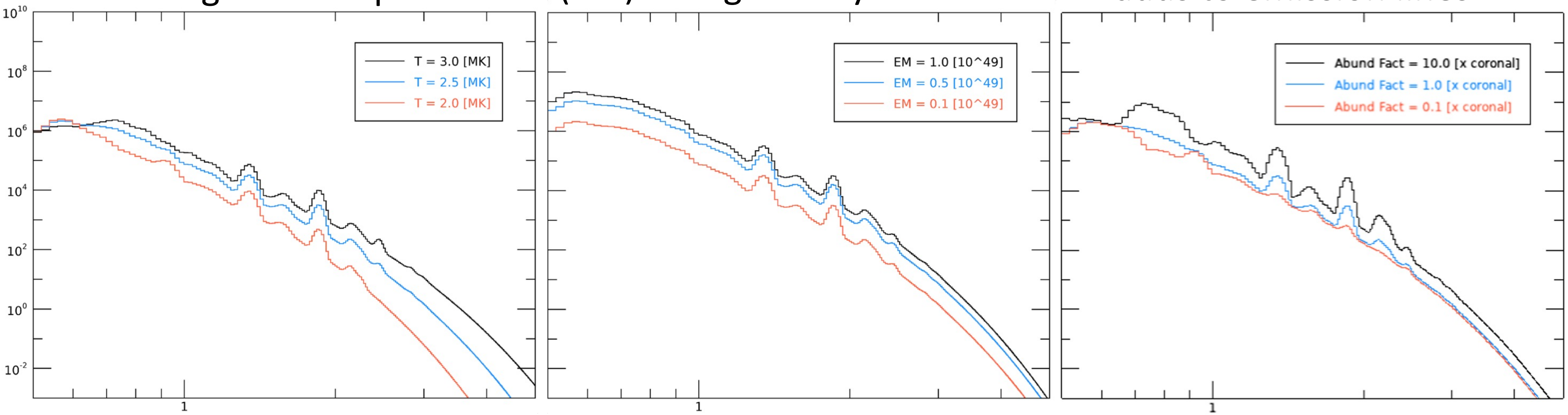
Fitting Model Spectra Provide Corona Temperature, Emission Measure, and Elemental Abundances

- Uses large CHIANTI database to create a spectral fit with free parameters Temperature, Emission Measure, and relative elemental abundances

Adjusting Temperature (T) changes the slope*

Adjusting Emission Measure (EM) changes the y offset*

Adjusting Abundance Factor (AF) adds to emission lines*



Photon Energy [keV]

*Note that T, EM, and AF are not completely independent of one another

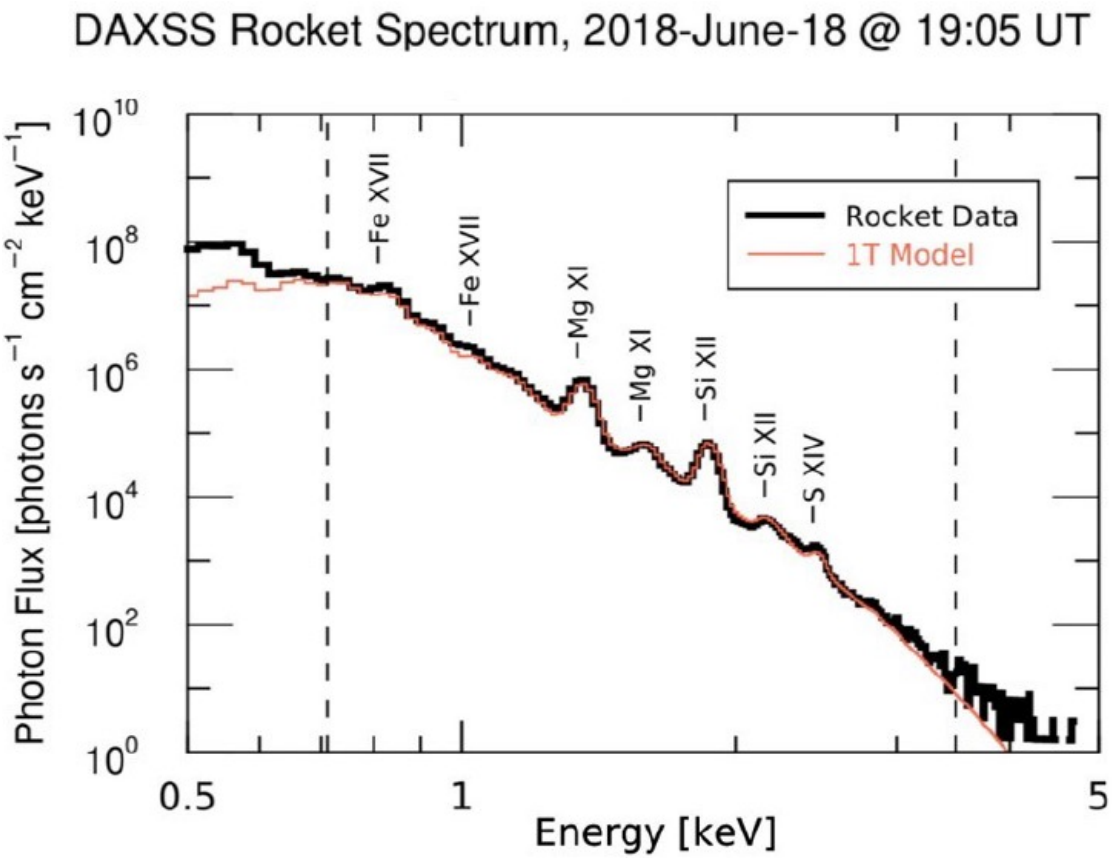
1T, 1EM, Singular AF Model

- Fit range is between 0.7 - 3.5 keV (Vertical Dashed Lines)
- The 1T model is the most simplistic but does not fit well over the whole energy range

1T Fit with Singular AF

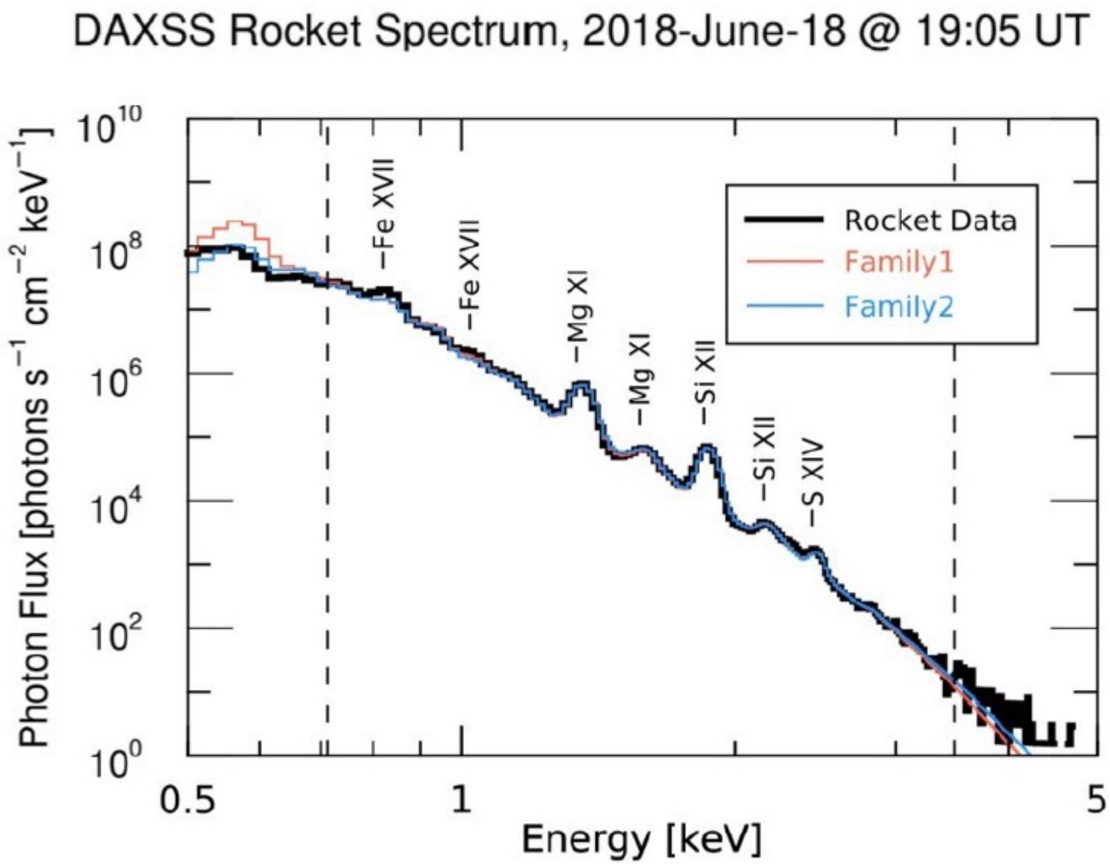
	T (MK)	EM ($e49\ cm^{-3}$)	AF ($\times$ FSEC)	Reduced Chi-Sq
Mean	2.85	0.129	0.91	7.7
Stdev	0.01	0.002	0.01	0.2

AF represents a singular abundance factor multiplied by Feldman Standard Extended Coronal (FSEC) values



2T, 2EM, Singular AF Model

- Fit range is between 0.7 - 3.5 keV (Vertical Dashed Lines)
- Fits the continuum better across the whole energy range better than a 1T model
  - Still lacking in some areas close to Fe emission lines
- We are seeing two families of fits emerge that each produce similar spectra and could describe coronal conditions



When 2 T, 2EM Are Introduced We See Two Families of Fits

- These families arise because our model is sampling coronal plasma at only two temperature points
- We see two families of fits with similar Chi-Sq values emerge, representing different points along the differential emission measure curve

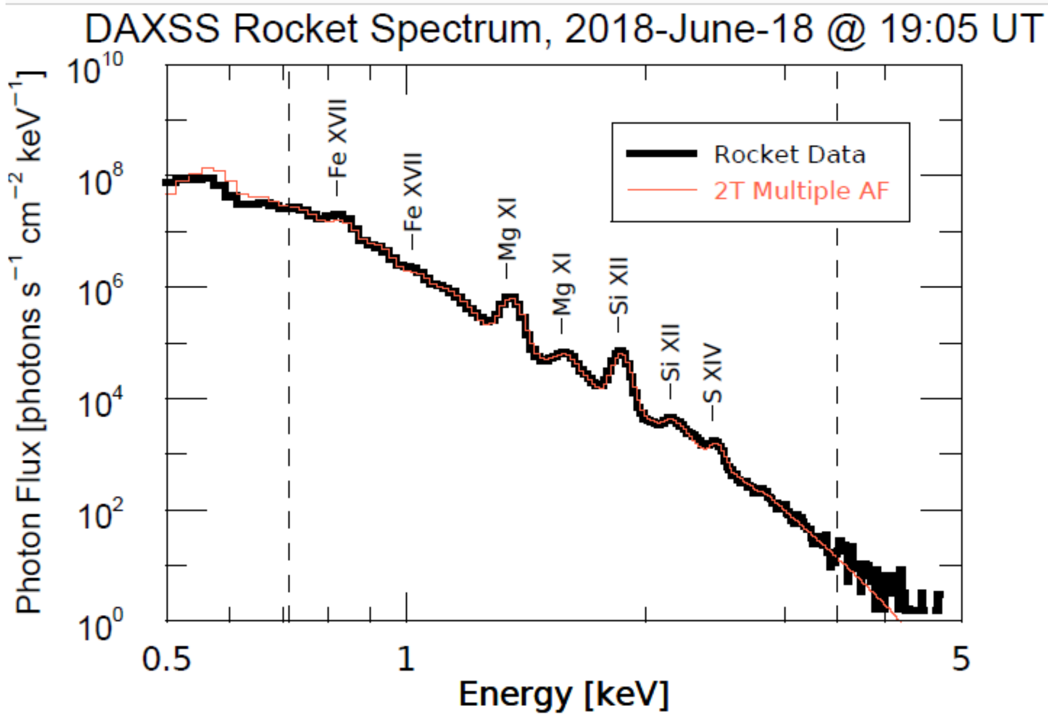
DAXSS Solar SXR Model Measurements with Singular Abundance Factor

	T1 (MK)	EM1 ($e49\ cm^{-3}$)	T2 (MK)	EM2 ($e49\ cm^{-3}$)	AF ($\times$ FSEC)	Reduced Chi-Sq	Percentage (%)
Family 1 Mean	1.59	1.11	3.14	0.061	1.07	4.5	48.9
Family 1 Stdev	0.01	0.04	0.02	0.002	0.01	0.2	
Family 2 Mean	2.10	0.35	3.48	0.026	1.02	4.9	50.3
Family 2 Stdev	0.01	0.01	0.04	0.002	0.01	0.2	

The Percentage column represents out of 1,000 fits how many fell into each family

2T, 2EM, Multiple AF Model

- Variable parameter abundances of four identiable low-FIP elements:
  - Mg, Si, S, and Fe
- Only one family
- Fit range is between 0.7 and 3.5 keV (Vertical Dashed Lines)
- Shows best agreement with measured spectrum over the entire fit range

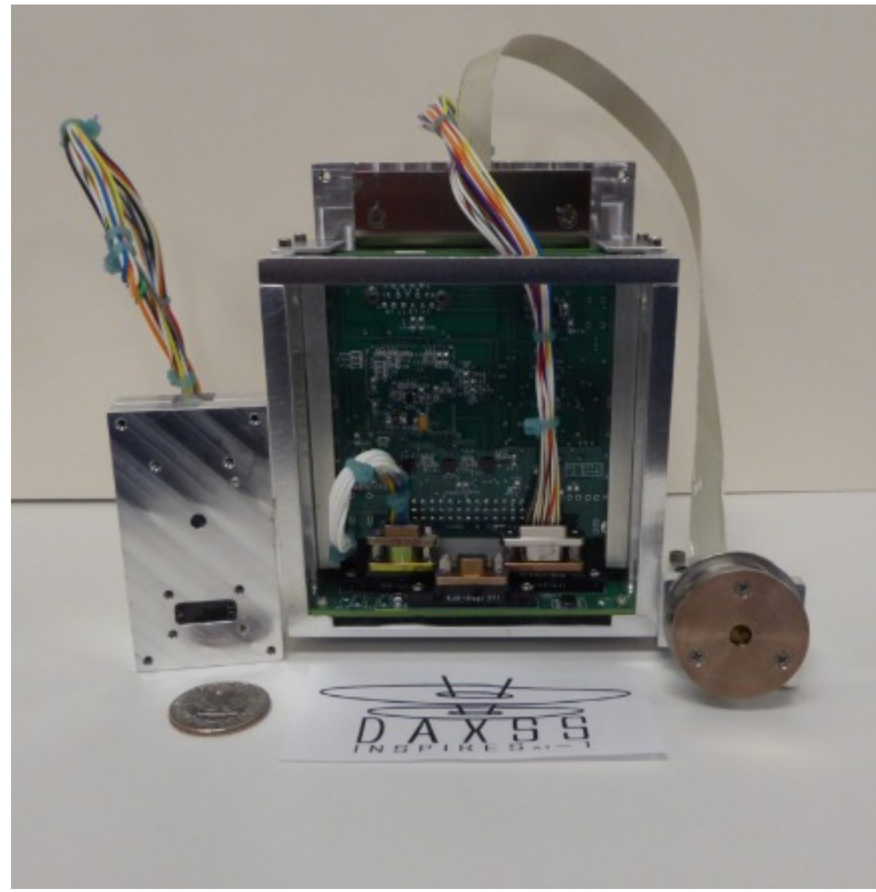


DAXSS Solar SXR Model Measurements with Abundance Factor for Identifiable Elements

	T1 (MK)	EM1 ($e49\ cm^{-3}$)	T2 (MK)	EM2 ($e49\ cm^{-3}$)	Mg AF (× FSEC)	Si AF (× FSEC)	S AF (× FSEC)	Fe AF (× FSEC)	Reduced Chi-Sq
Mean	1.86	0.50	3.29	0.043	1.02	0.99	1.00	1.35	3.9
Stdev	0.02	0.02	0.03	0.003	0.01	0.02	0.05	0.02	0.2

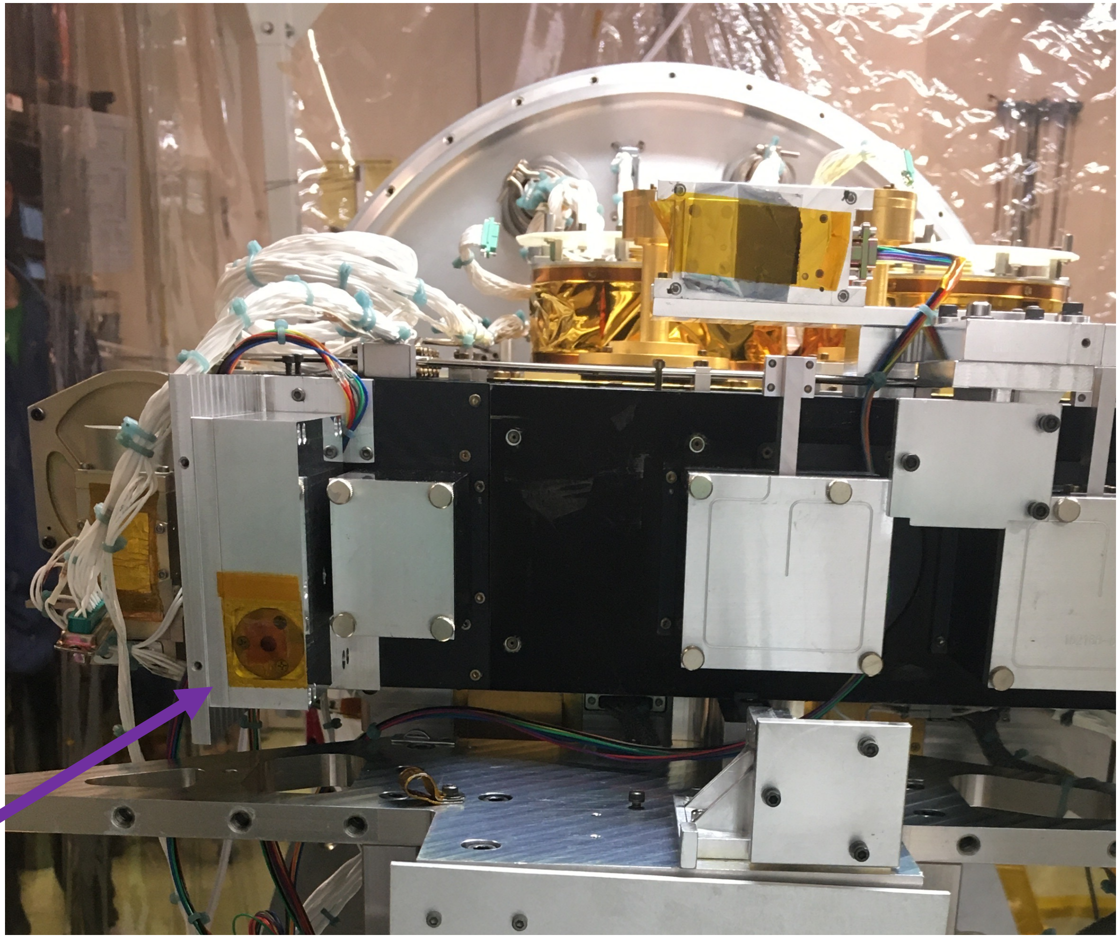
DAXSS is Now On Orbit!

- DAXSS has been collecting data since late Feb, 2022
- Very exciting data
  - Many flares downlinked
  - Some quiescent sun data also



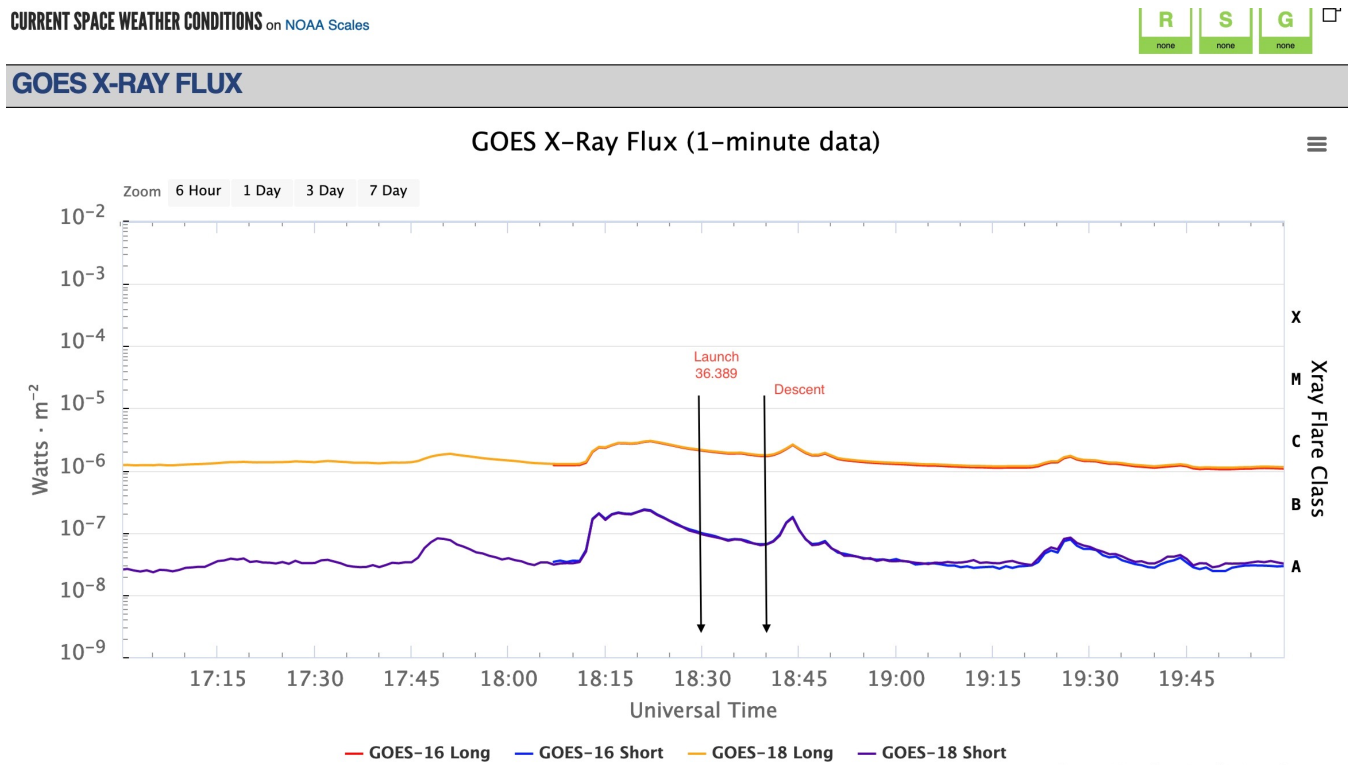
DAXSS-2 was Flown on Recent 2023 Rocket EVE Flight

- The new, smaller packaged version of the X123 called the X55 was flown as DAXSS-2.
- Same dual aperture design as DAXSS, with extended sensitivity into the higher energies

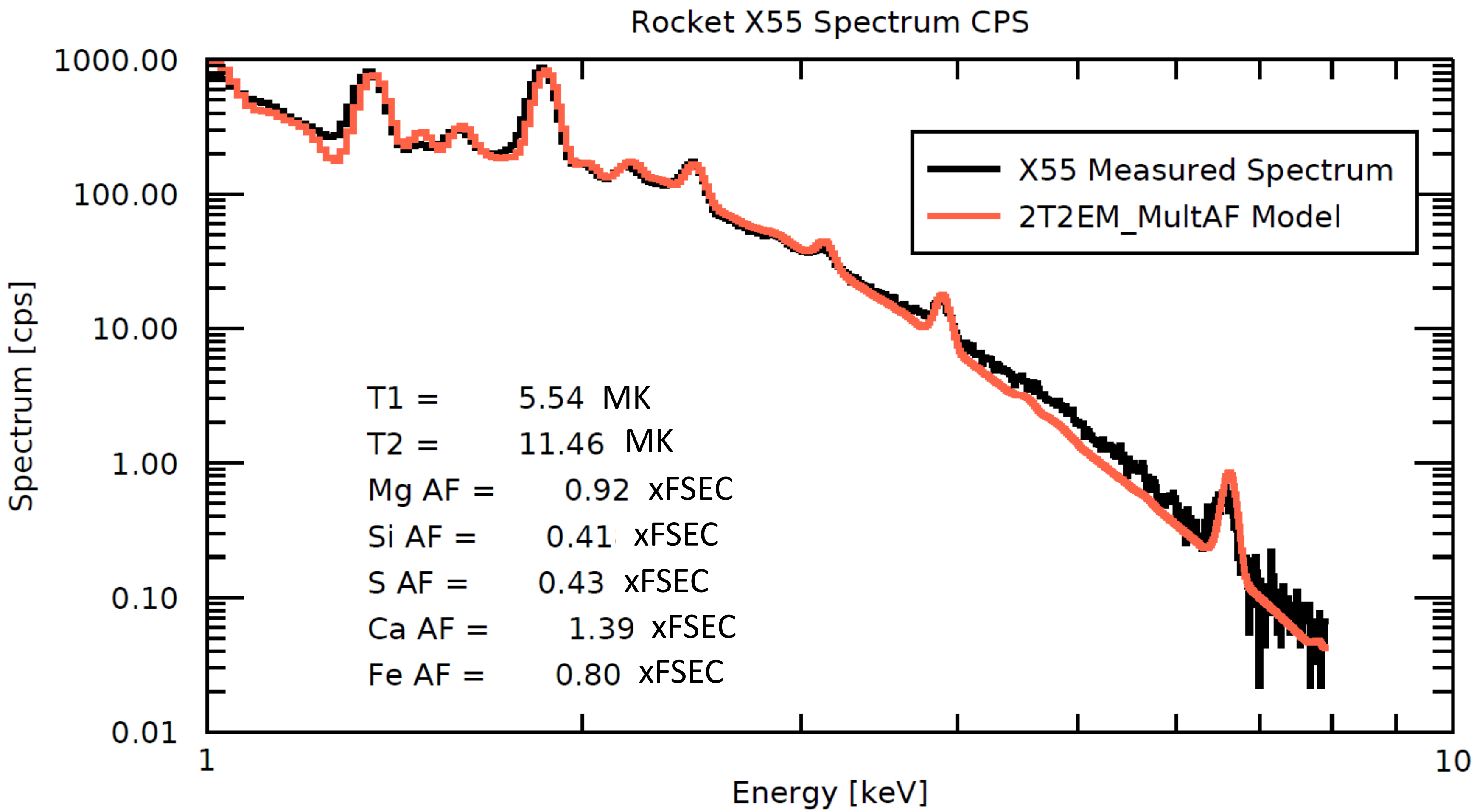


GOES X-rays during flight

- X-ray flux started near C2.1 at launch time and decreased to C1.7
- Sun was active with 6 M-class flares, ~15 C-class flares, and long channel irradiance was > C1 class for entire day.



Preliminary Results From 3 May 2023 Sounding Rocket



Discussion of Results from DAXSS Spectra

- QS Abundances of Mg, Si, and S are within 2% of FSEC abundance values

- Fe abundance was found to be higher than FSEC abundance by 35%
  - Possibly the 2T, 2EM, Multiple AF model is too simplistic and may not accurately represent the temperature contributions in the spectrum
  - There could be missing elemental emission lines in the CHIANTI line database near for the given energies
  - The abundance of Fe could actually be higher than the FSEC value, although this would go against many prior measurements

- To solve this discrepancy additional high-resolution, high-sensitivity, and long-term systematic measurements from instruments in this energy range are needed

- MinXSS-1 flew an earlier model of the X123 spectrometer and accumulated data over a year long mission
  - This model fitting code can be applied to MinXSS-1 data as well

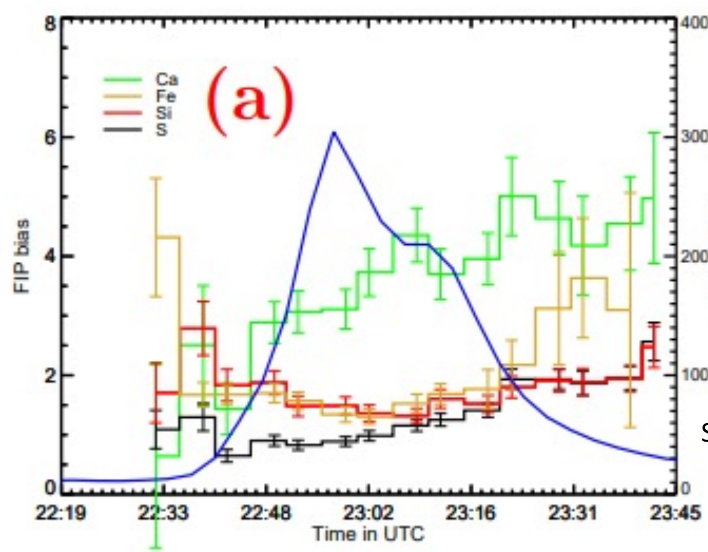
Other Analyses of Flare Abundance Changes

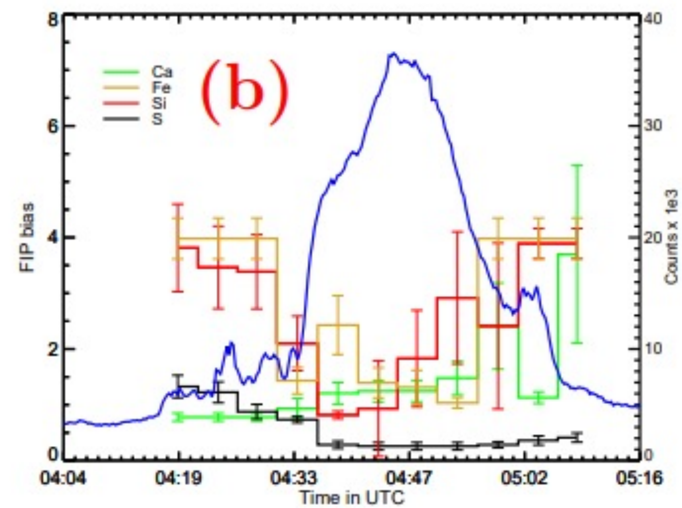
- Low FIP elements such as Ca, Fe, and Si are usually 4 times more abundant in the corona than the chromosphere and S is usually 2 times more abundant

* Feldman 1992, Landi 2002

- During a flare this FIP bias changes and abundances shift towards chromospheric

* Narendranath 2020, Mondal 2021



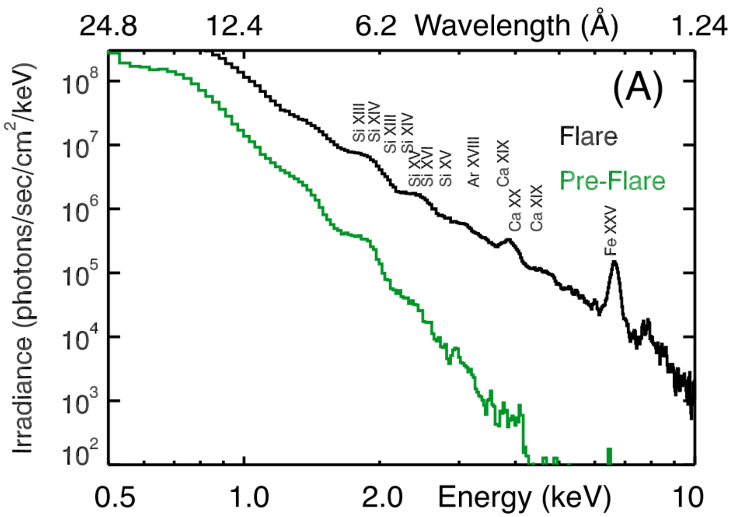


Source: Narendranath 2020, https://arxiv.org/pdf/2011.08584.pdf

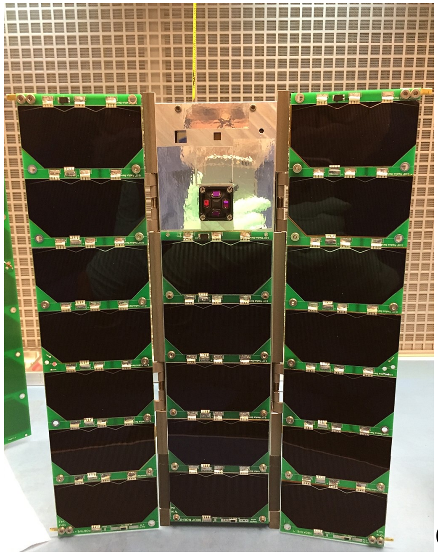
Figure 5. FIP bias variation for the flares on (a) 6 January 2014 (data in Figure 3) (b) 1 May 2004 (data in figure 4) for Ca, Fe, Si and S . The light curve in the 2-10 keV energy range is plotted in blue. The recovery rates are observed to be different.

MinXSS-1 CubeSat

- Obtained on-orbit solar SXR spectra between 0.5 – 30 keV
- Data spans from 2016 June to 2017 April, the tail end of solar minimum
- Captures the continuum as well as several emission line features
- Both quiescent sun conditions as well as solar flare data are observed



Credit: Tom Woods



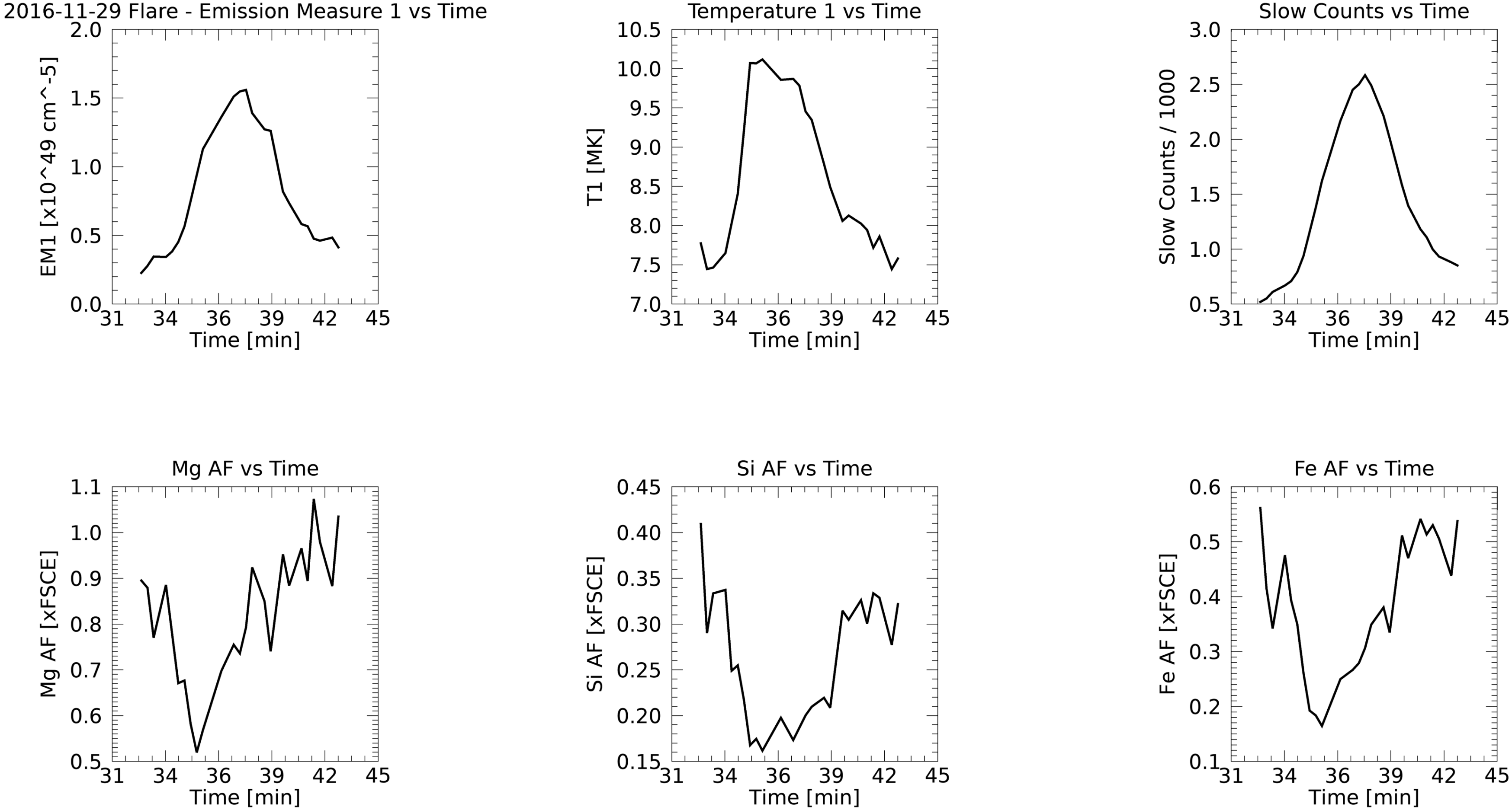
Credit: James Mason

MinXSS-1 Flares Analyzed

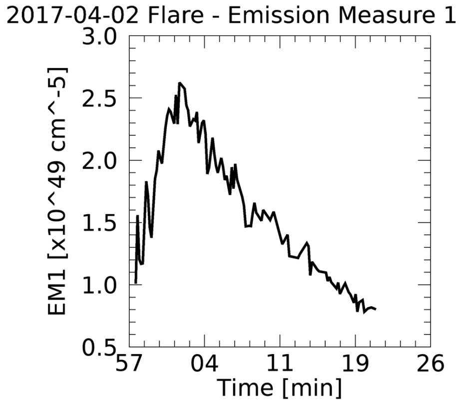
	Date	GOES Peak Time	Flare Class	Maximum Temperature	Flare Type
1	2016-11-29	23:38 UTC	M1.2	10.1 MK	Compact Flare
2	2017-04-02	13:00 UTC	M2.3	14.5 MK	Long-Decay Flare
3	2016-07-24	14:04 UTC	C6.9	9.6 MK	QPP Flare

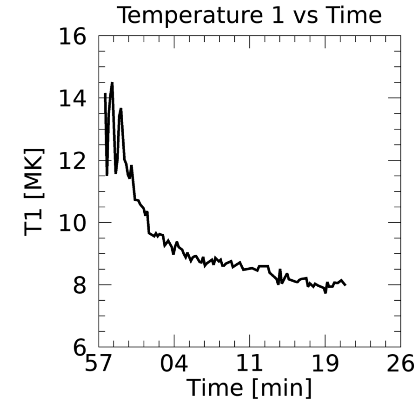
- A single T, single EM model with separate AF for Mg, Si, and Fe was used
- Many questions to investigate:
  - Is the decrease in AF consistent for all types of flares?
  - Is the maximum T reached dependent on flare class?
  - When is the maximum T observed relative to the flare peak?
  - When is the minimum AF observed relative to flare peak?

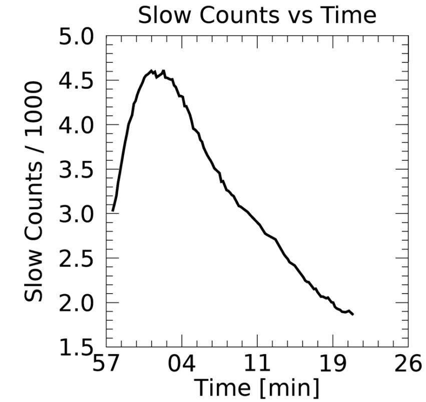
Flare 1 – Compact Flare

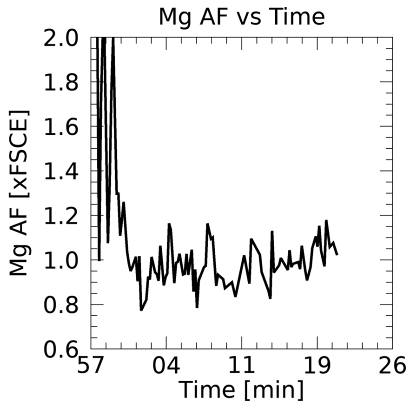


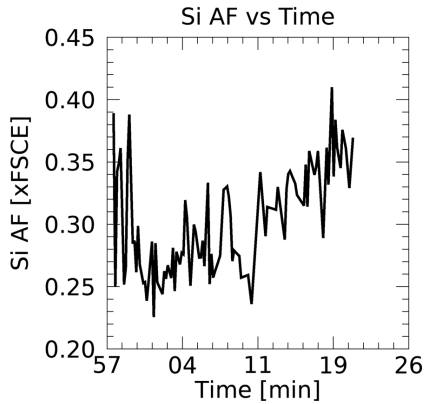
Flare 2 – Long-Decay Flare

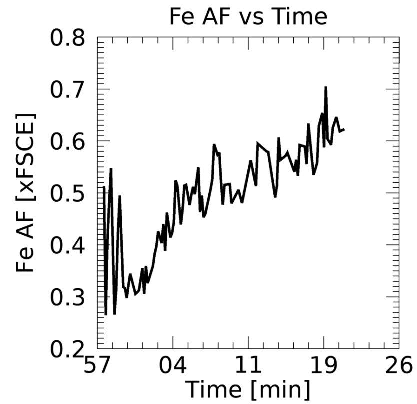




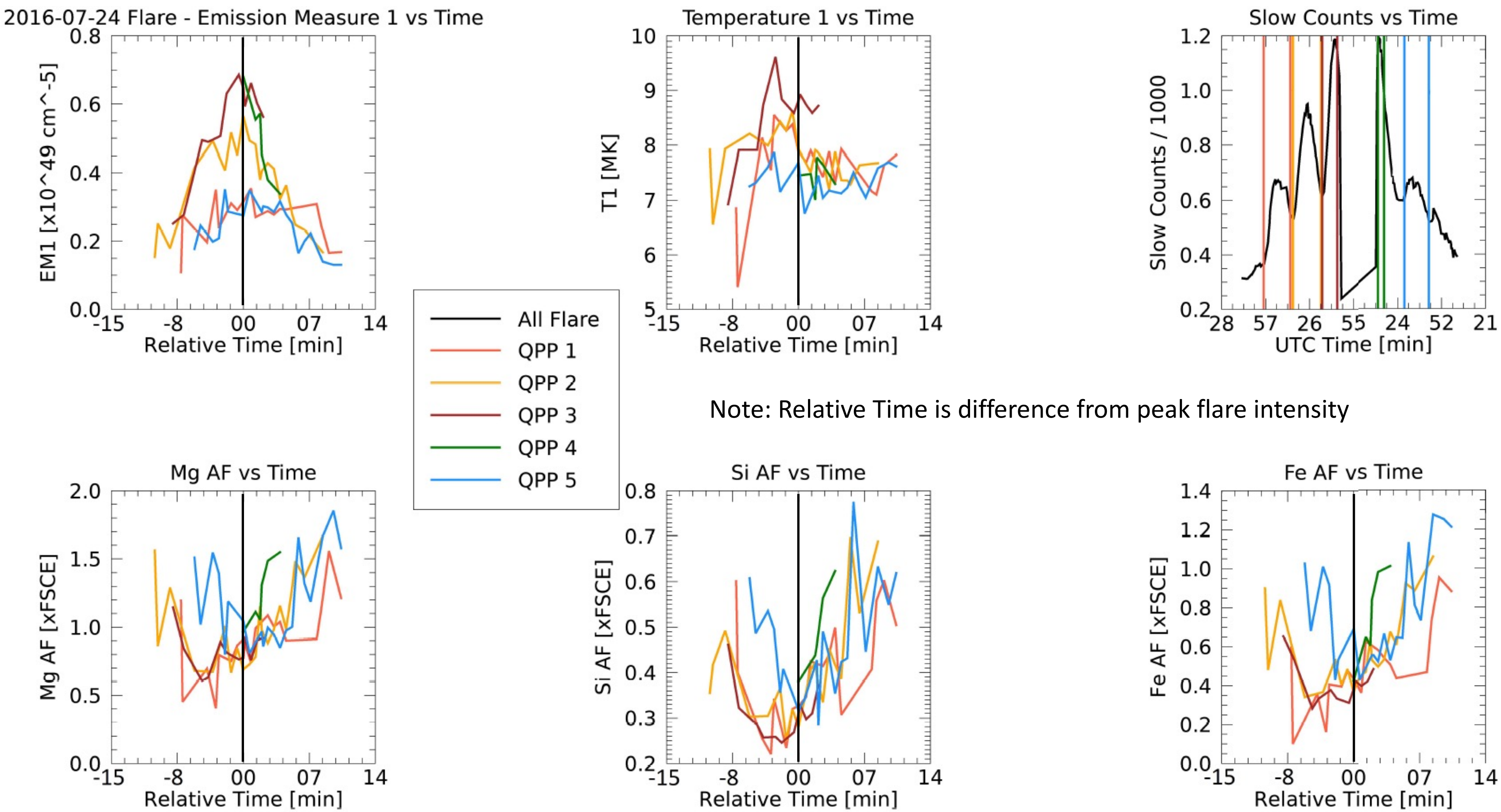








Flare 3 – Quasi-Periodic Pulsation (QPP) Flare



Note: Relative Time is difference from peak flare intensity

Conclusions from Flare Analysis

- Is the decrease in AF consistent for all types of flares?
  - Yes, the decrease in AF was found for the three different flares analyzed that differed in magnitude as well as type

- Is the maximum T reached dependent on flare class?
  - Yes, for higher magnitude flares the maximum temperature reached by the SXR emitting plasma increased as well

- When is the maximum T observed relative to the flare peak?
  - The temperature peak for the flare occurs about 3 minutes <u>prior</u> to the flare peak in intensity

- When is the minimum AF observed relative to flare peak?
  - The minimum AF reached also occurs about 3 minutes <u>prior</u> to the flare peak in intensity.

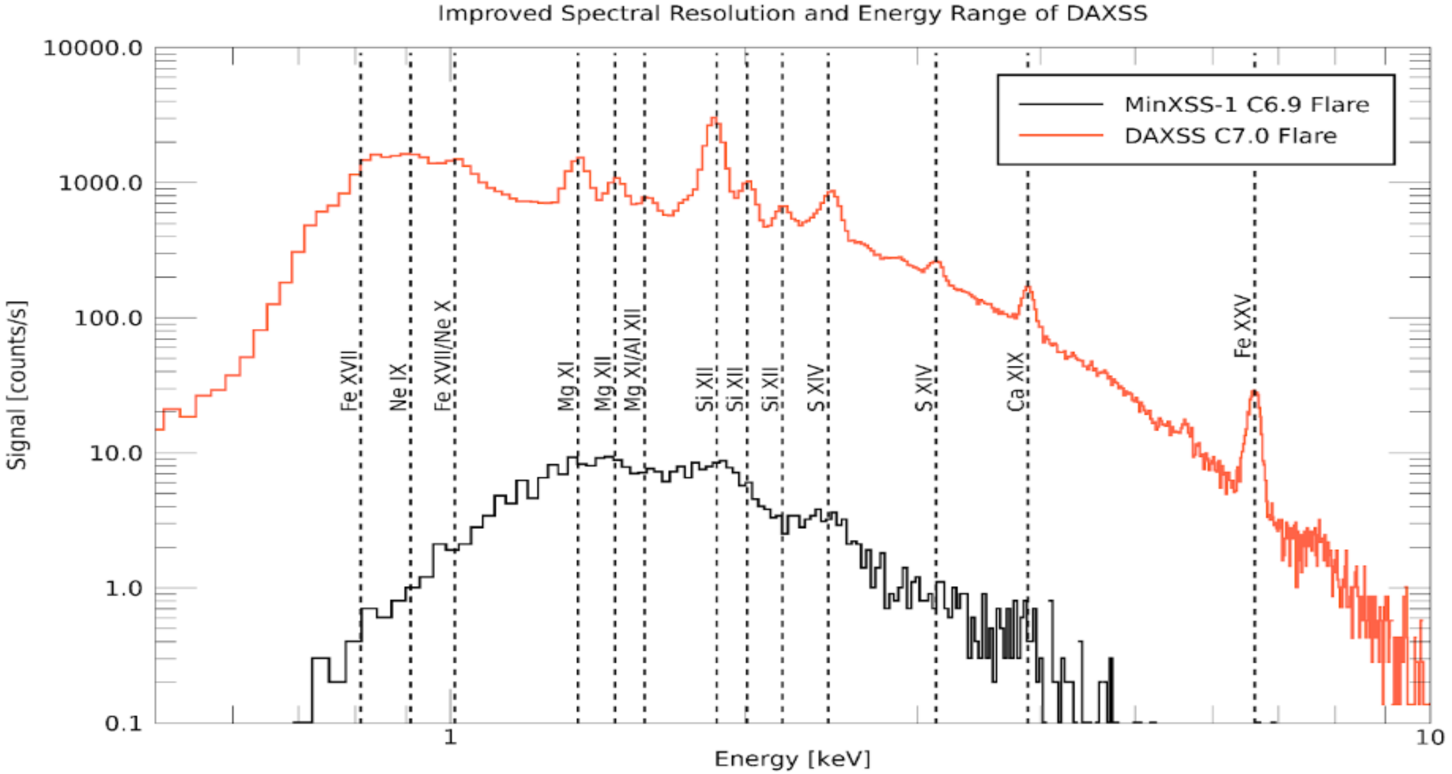
How Do These Results Help Answer the Key Science Question?

Which heating mechanisms are dominant in making the solar corona more than 100 times hotter than the photosphere?

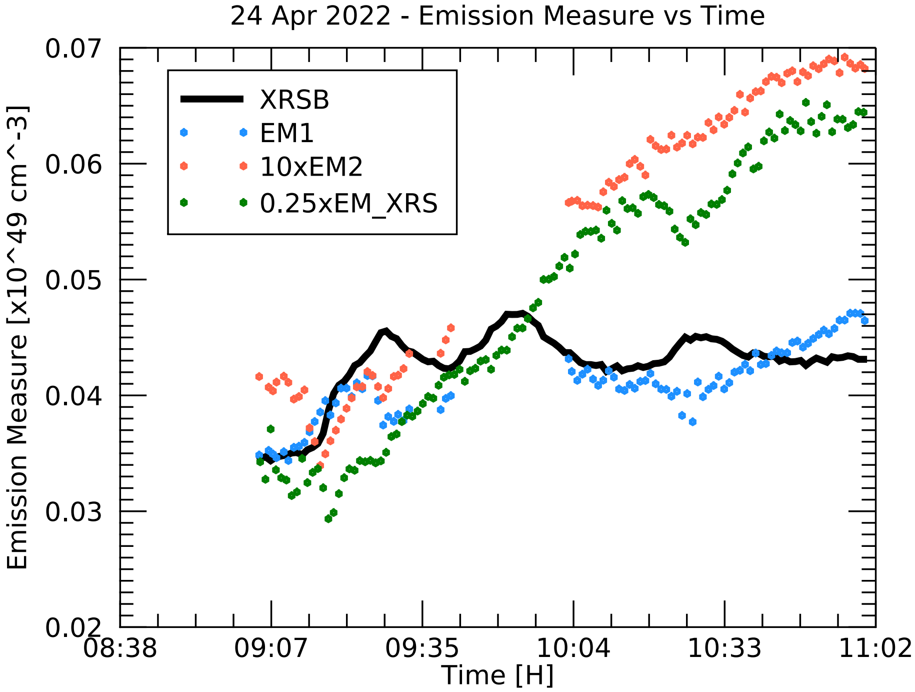
- The decrease in AF during the start of the gradual phase is strong supportive evidence of chromospheric evaporation caused by magnetic reconnection heating of the corona.
- Increases in maximum temperature reached by the SXR emitting plasma for higher magnitude flares implies that higher energy flares provide more heating to the corona than lower energy flares.
- The temperature peak indicates that the chromospheric plasma is hottest 3 minutes before the majority of the energy is emitted through SXR radiation.
- Minimum AF values reached 3 minutes prior to the flare peak shows that the SXR radiation is coming from plasma that underwent chromospheric evaporation.

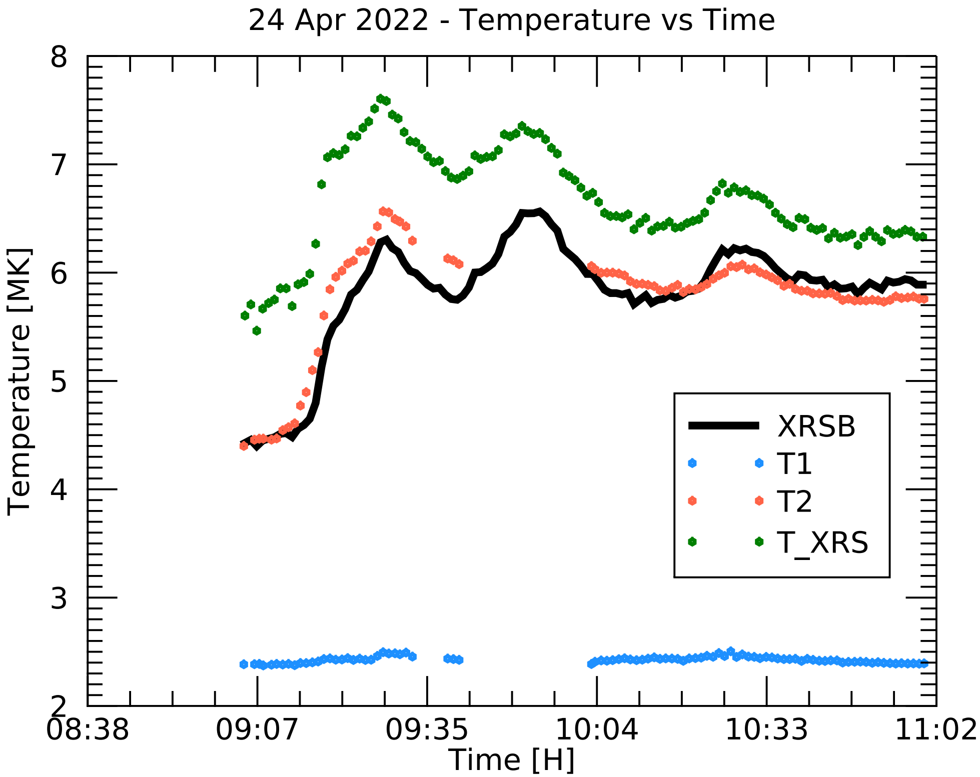
DAXSS Data are Available

- DAXSS data have much better spectral resolution and an increased sensitivity to higher energies
  - Better science! Lower uncertainties and more visible emission lines



DAXSS Flare Analysis Results - EM and T vs Time





Tom Eden’s Model

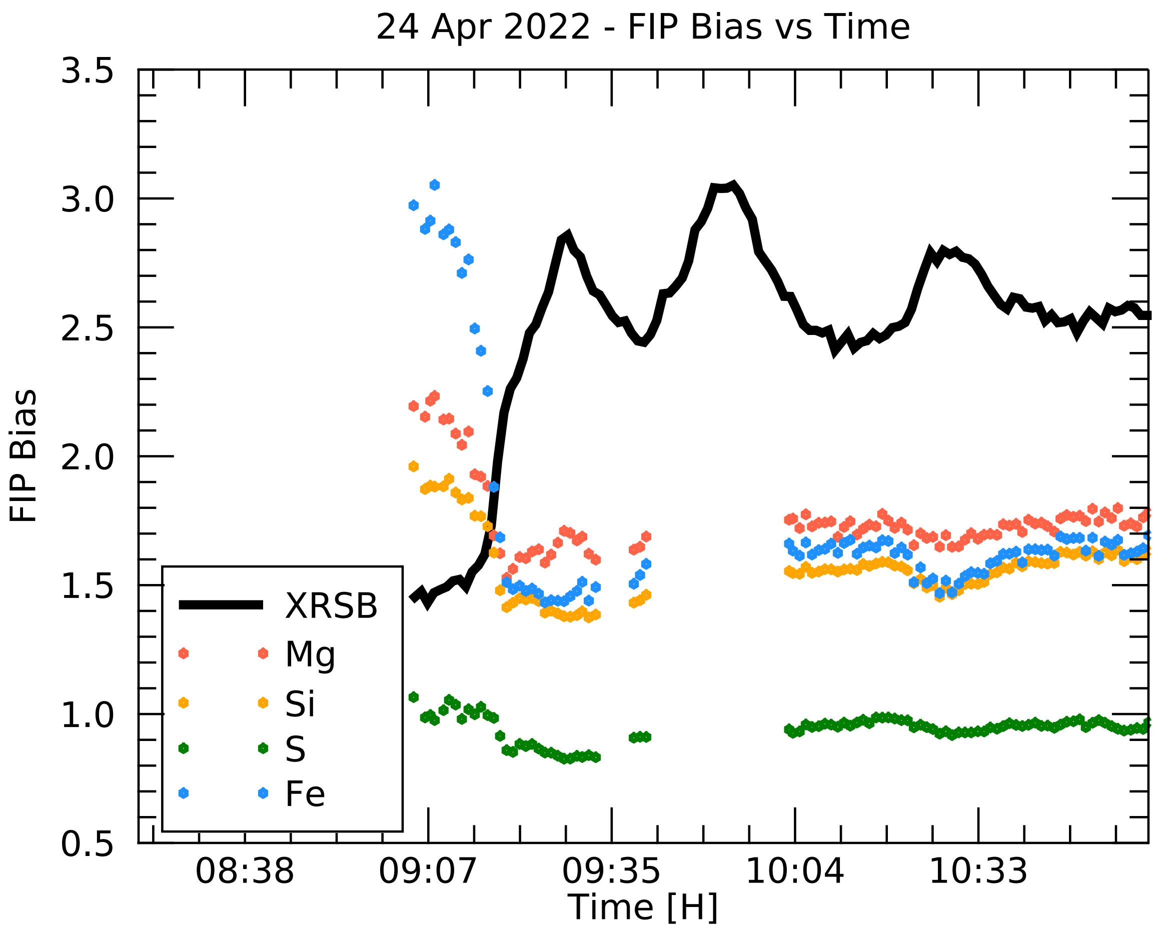
$$T_{XRS}(MK) = 2.7460 + 129.47 \cdot R - 966.28 \cdot R^2 + 5517.5 \cdot R^3 - 1.8664x10^4 \cdot R^4 \quad (1)$$
$$+3.5951x10^4 \cdot R^5 - 3.6099x10^4 \cdot R^6 + 1.4687x10^4 \cdot R^7$$

$$B_{model} = 6.9469 - 6.0827 \cdot T_{XRS} + 1.7364 \cdot T_{XRS}^2 - 0.15594 \cdot T_{XRS}^3 \quad (2)$$
$$+6.7848x10^{-3} \cdot T_{XRS}^4 - 1.4446x10^{-4} \cdot T_{XRS}^5 + 1.2089x10^{-6} \cdot T_{XRS}^6$$

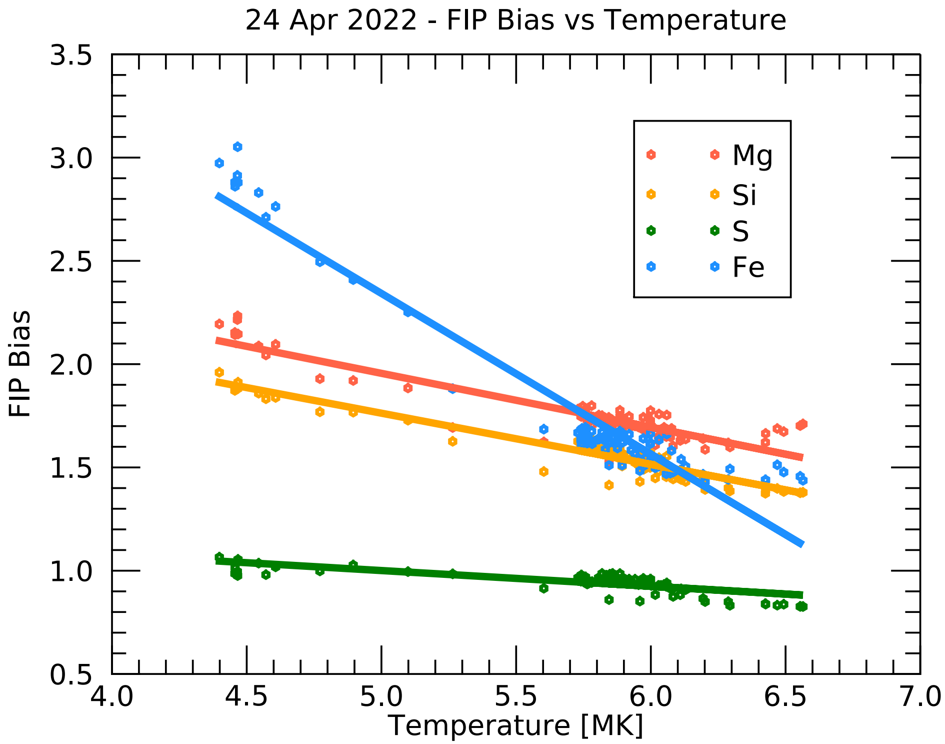
$$EM_{XRS}(10^{55}\ cm^{-3}) = B_{measure}/B_{model} \quad (3)$$

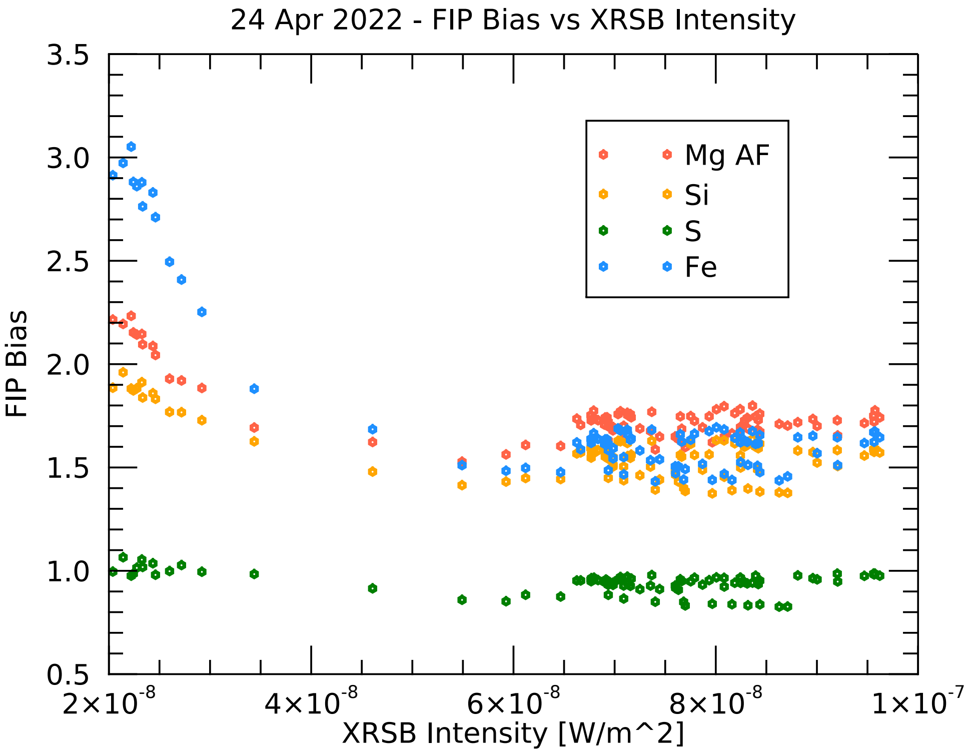
Where R = GOES XRS A/B ratio

DAXSS Flare Analysis Results - FIP Bias vs Time



DAXSS Flare Analysis Results - FIP Bias vs T and XRSB Intens.





Thank you!

Delivery of the MinXSS-2 CubeSat

Rocket EVE Operations

Rocket EVE on the Launch Pad

Underflight Calibrations at SURF

Recovery of Rocket in Blackhawk Helicopter

Meteor Radar Experiment in Antarctica