Study of solar elemental abundances evolution during solar flares using satellite-based soft X-ray measurements

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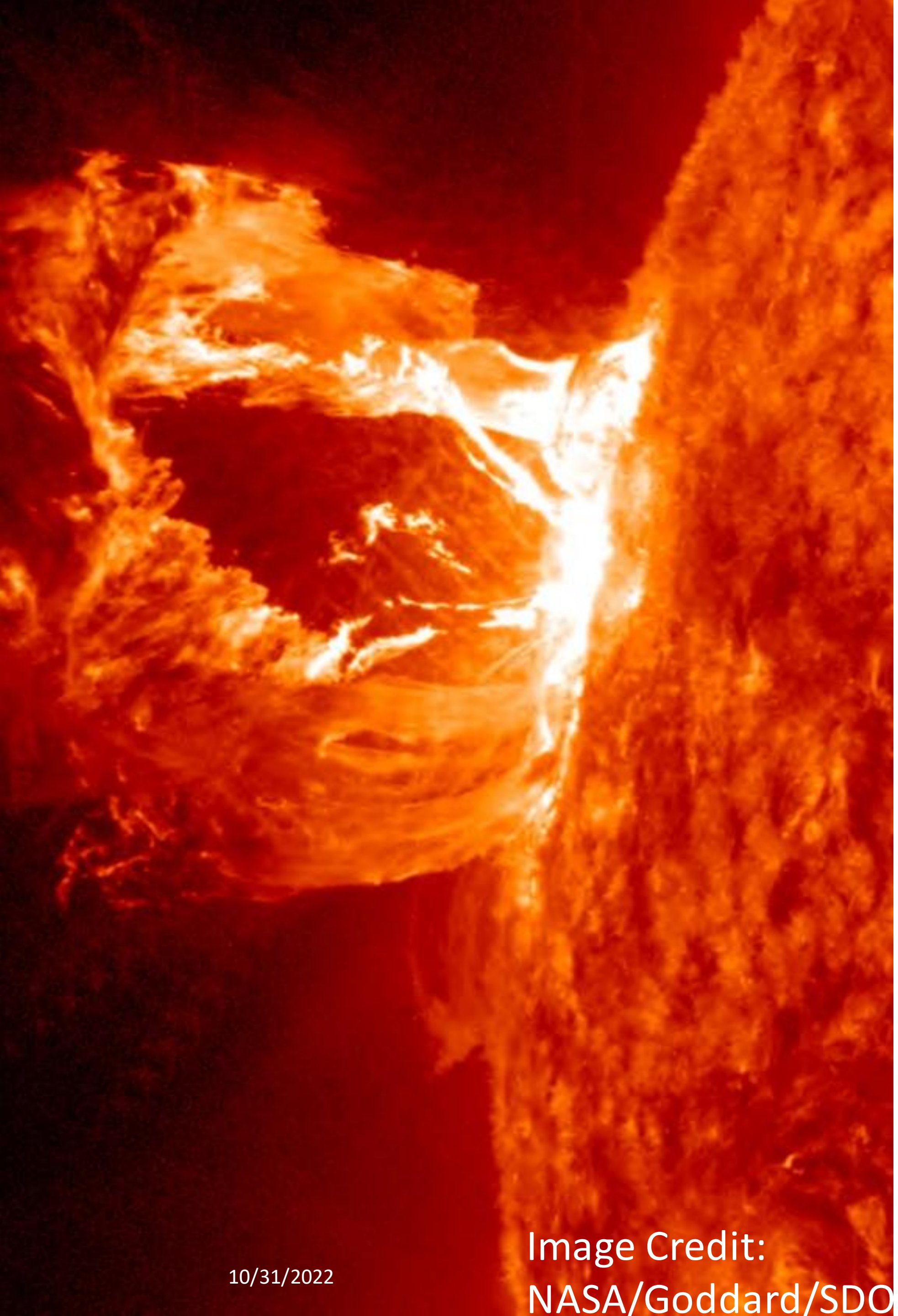
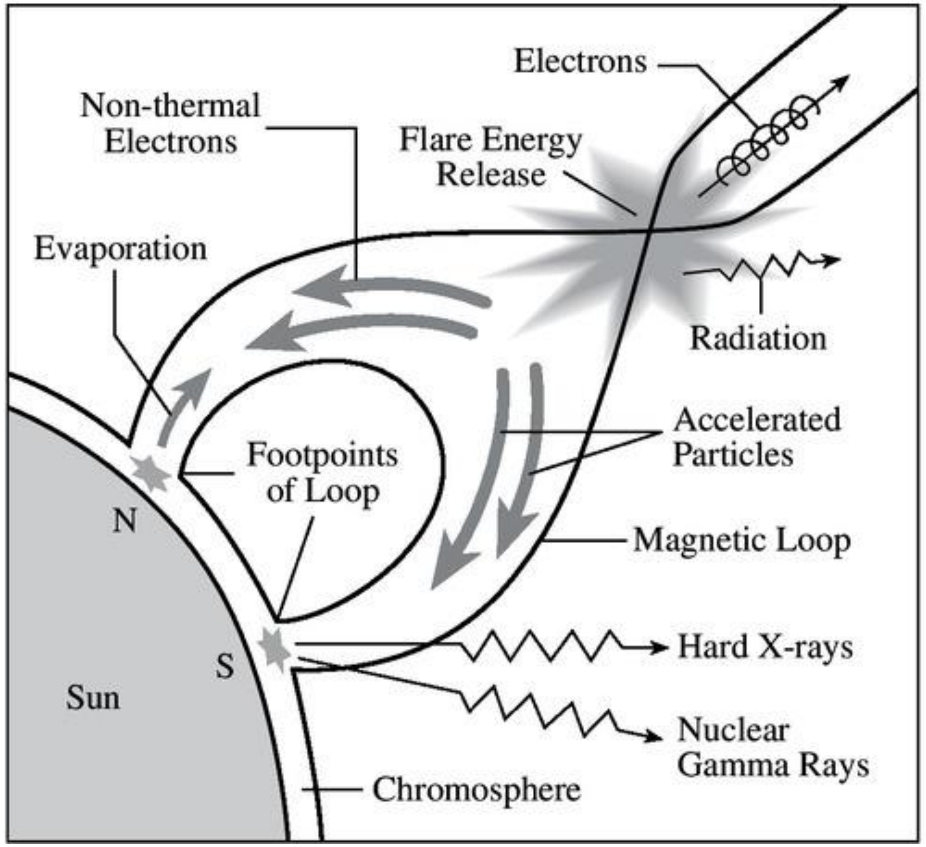


Introduction

- Solar flares are violent energetic releases of stored magnetic energy from the Sun, originating from the solar corona.
- Understanding the processes driving solar flares are important due to their impact on space weather, ionosphere, and their association with coronal mass ejections (CME).
- The emission associated with the flares peaks in the soft X-ray regime (0.1 - 10 nm) as the corresponding temperature is 10 MK over the coronal background temperature of 1 MK.
- This makes soft X-rays an excellent probe into the hot, low density plasma, particularly in Corona and flares.

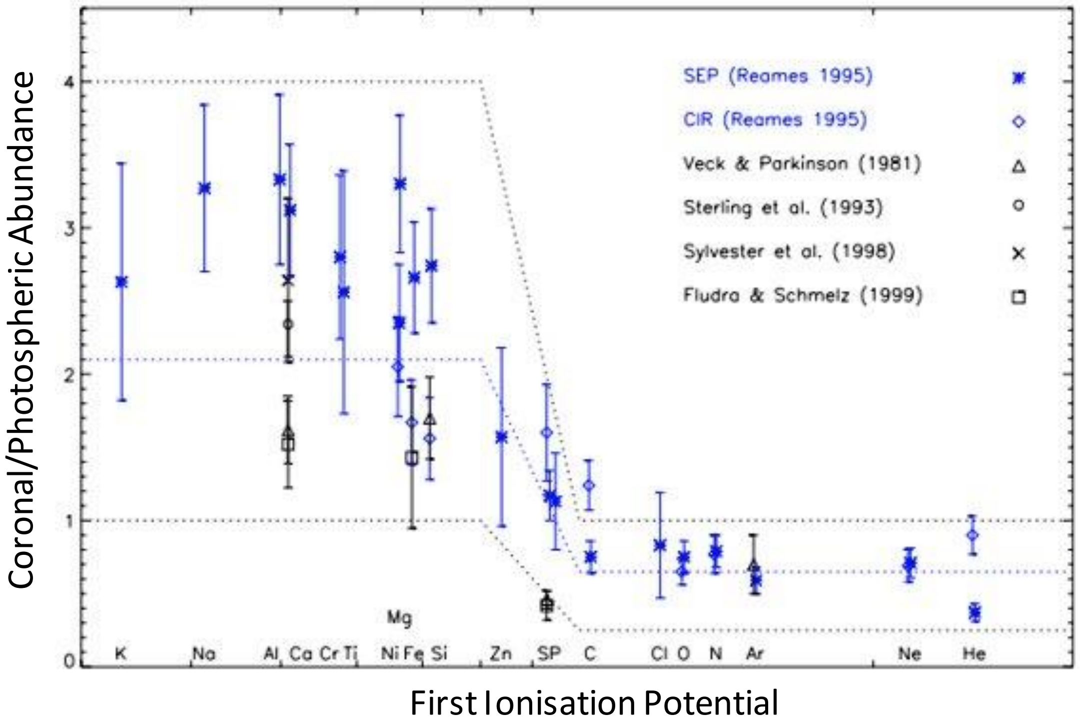
Introduction (cont.) The Standard Flare Model



Credit: Professor Kenneth R. Lang, Tufts University

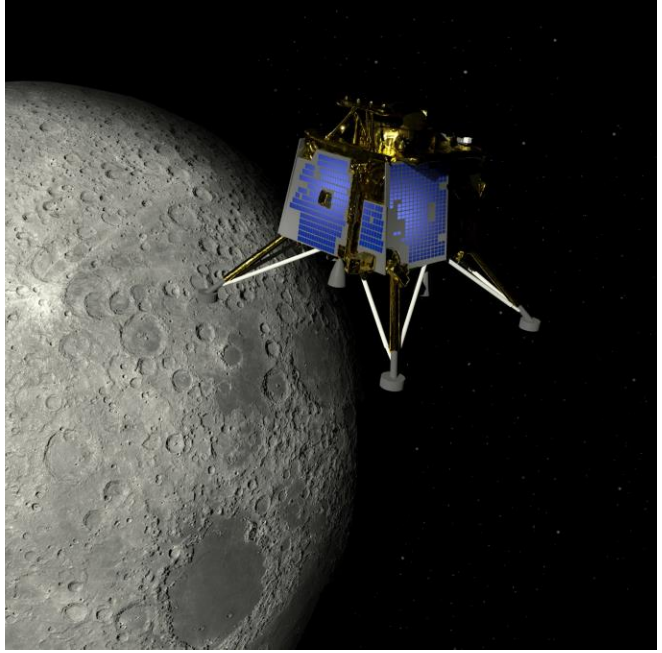
1. Magnetic reconnection happens at the top of the loop.
2. As the magnetic fields close down and reconnect, energy is released that goes into accelerating electrons which travel down the magnetic field lines (radio emission).
3. The e^- hit chromospheric foot points and heat up the chromospheric plasma (Hard X-ray emission).
4. Heated chromospheric plasma evaporates into corona and fill the loop (soft X-ray).

Relevance



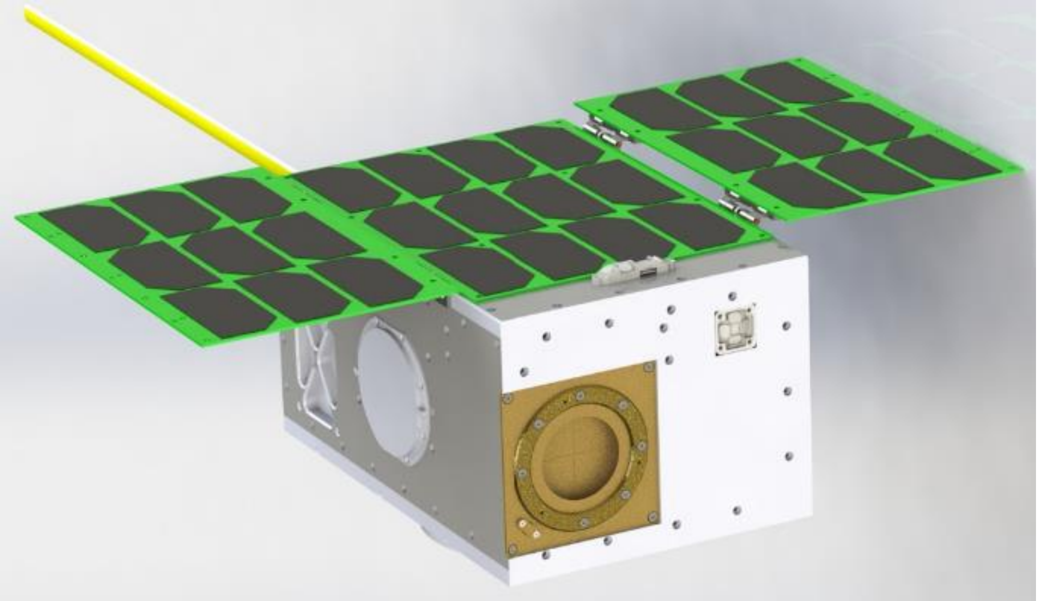
Source: J T Shmelz *et al,* 2012

- Soft X-ray emissions from the loop originates from the evaporated, hot chromospheric plasma.
- **The composition should evolve from coronal to chromospheric during the flare duration.**
- Low First Ionisation Potential (FIP) elements should show more prominent variation in elemental abundances.
- In this study, we look into the evolution of elemental abundances during solar flares using satellite based soft X-ray measurements.
- The recent **XSM** (Solar X-ray monitor) onboard CHANDRAYAAN-2 (2019-) and **DAXSS** (Dual-zone Aperture X-ray Solar Spectrometer) onboard INSPIRESAT-1 (2022-), provide excellent opportunities to study the solar soft X-ray emission spectra.



XSM (Solar X-ray monitor) : CHANDRAYAAN –2

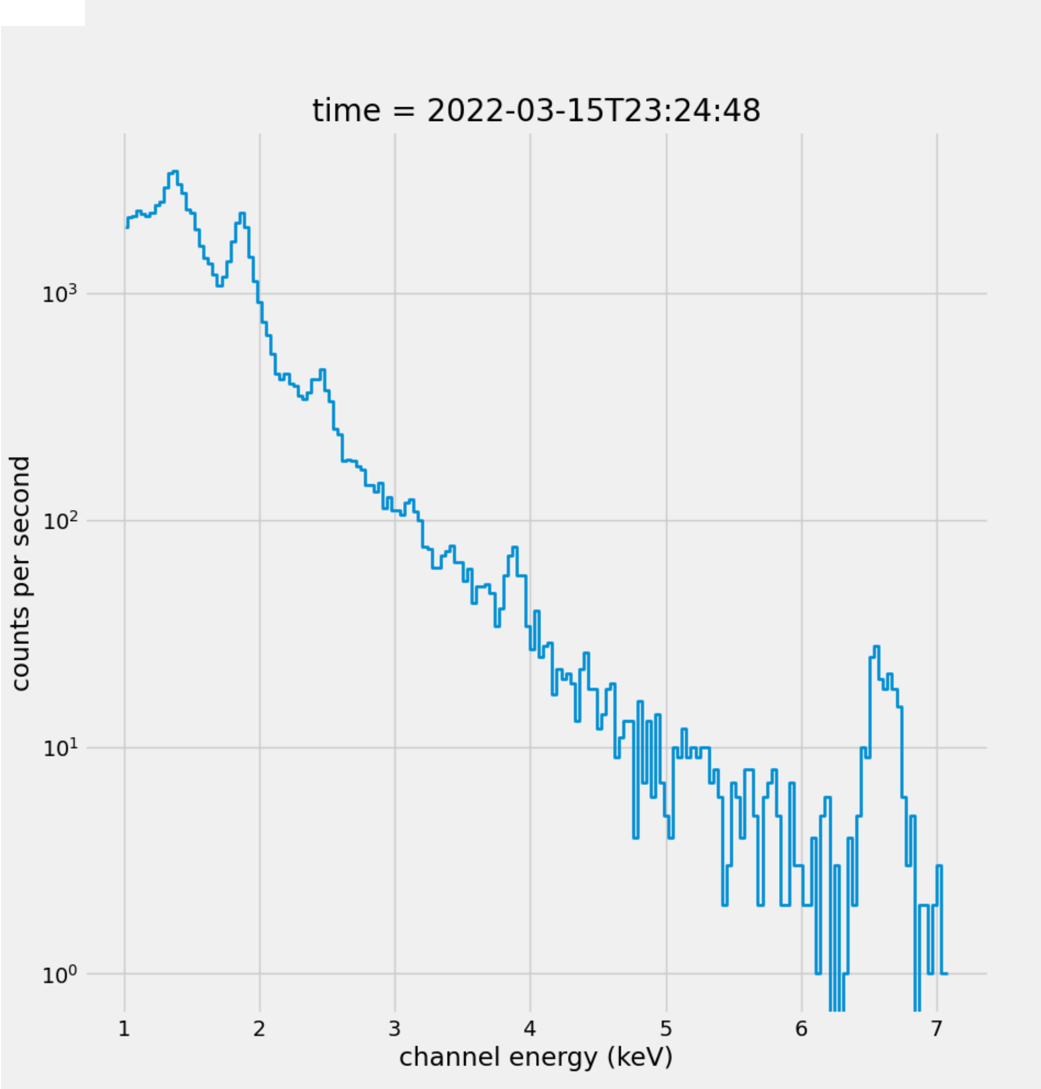
- Silicon Drift Detector (SDD)
- Energy Range : 1 – 15 keV (0.8 Å to 12 Å) in 512 channels.
- Spectral resolution ≈ 180 eV @ 5.9 keV
- 1-sec cadence.
- Can observe up to X-class flares.
- Provides support to Chandrayaan-2 Large Area Soft X-ray Spectrometer (CLASS)



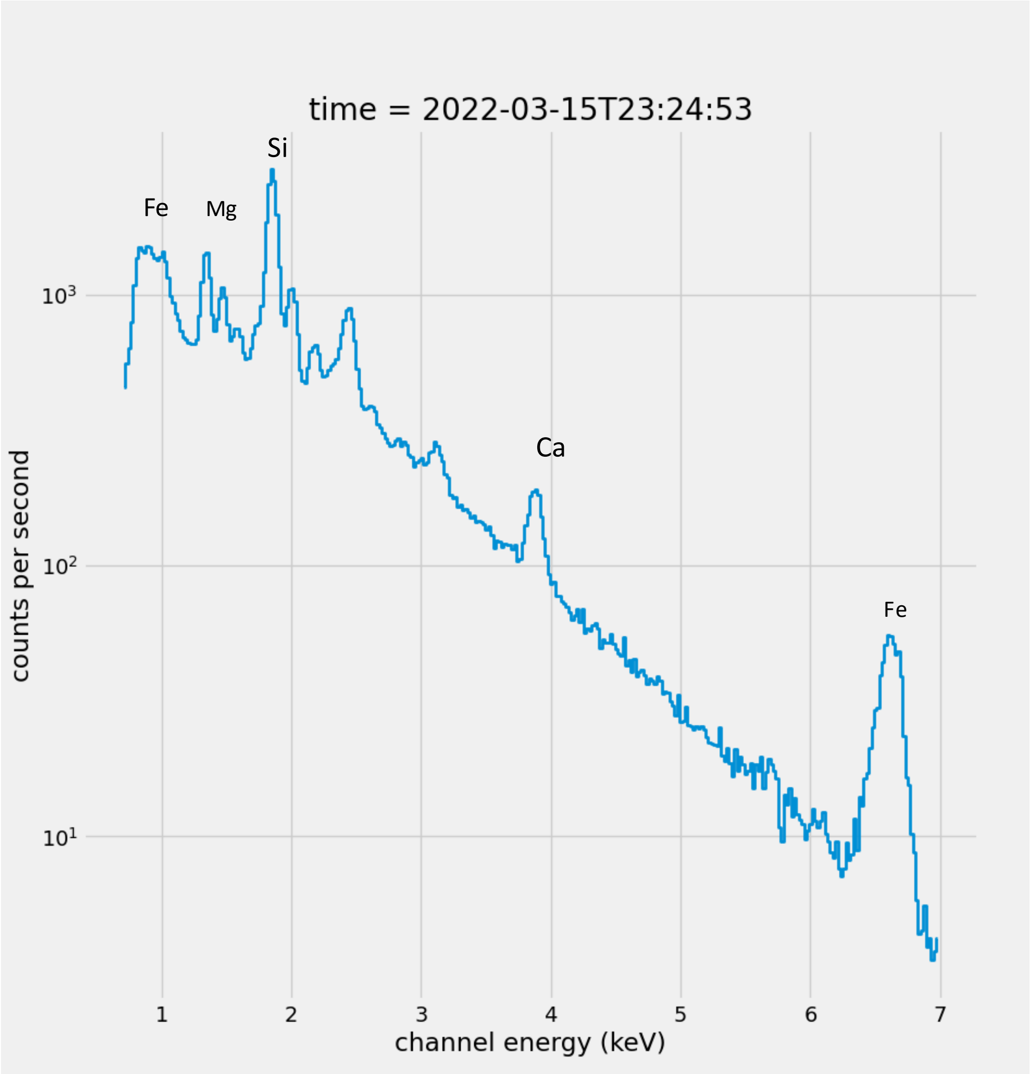
DAXSS (Dual-zone Aperture X-ray Solar Spectrometer) : INSPIRESAT-1

- Silicon Drift Detector (SDD)
- Energy Range : 0.5 keV - 20 keV (0.6 Å to 25 Å) in 1024 channels.
- Spectral Resolution : ≈ 150 eV
- 9-sec cadence.
- Sensitive up to M1 class flares.
- Continuation of MinXSS-1, MinXSS-2 missions.

Sample Solar Soft X-ray spectra

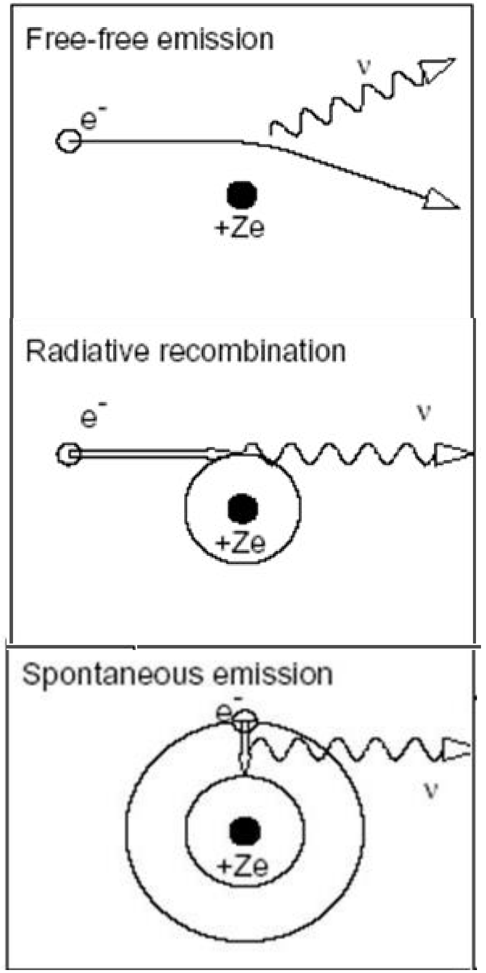


i) XSM Spectra during a flare



ii) DAXSS Spectra during a flare

Model Development



Flare Emission Modeling

The flare spectrum is modeled using isothermal plasma model.

- Primary emission mechanisms are **free-free** (Bremsstrahlung) radiation, free-bound (**Radiative recombination**) emissions and bound-bound (**spontaneous Emission & Decay**) emissions.
- The spectra will depend on Temperature, emission measure and abundances of individual elements.
- We used the CHIANTI atomic database to model the emissions as isothermal plasma emissions using CHIANTIpy.
- Direct calculations of individual spectra are computationally exhaustive, making it impractical for fitting to the data.
- A lookup table based approach is used to complete the calculations in a reasonable time.

Look up table based model

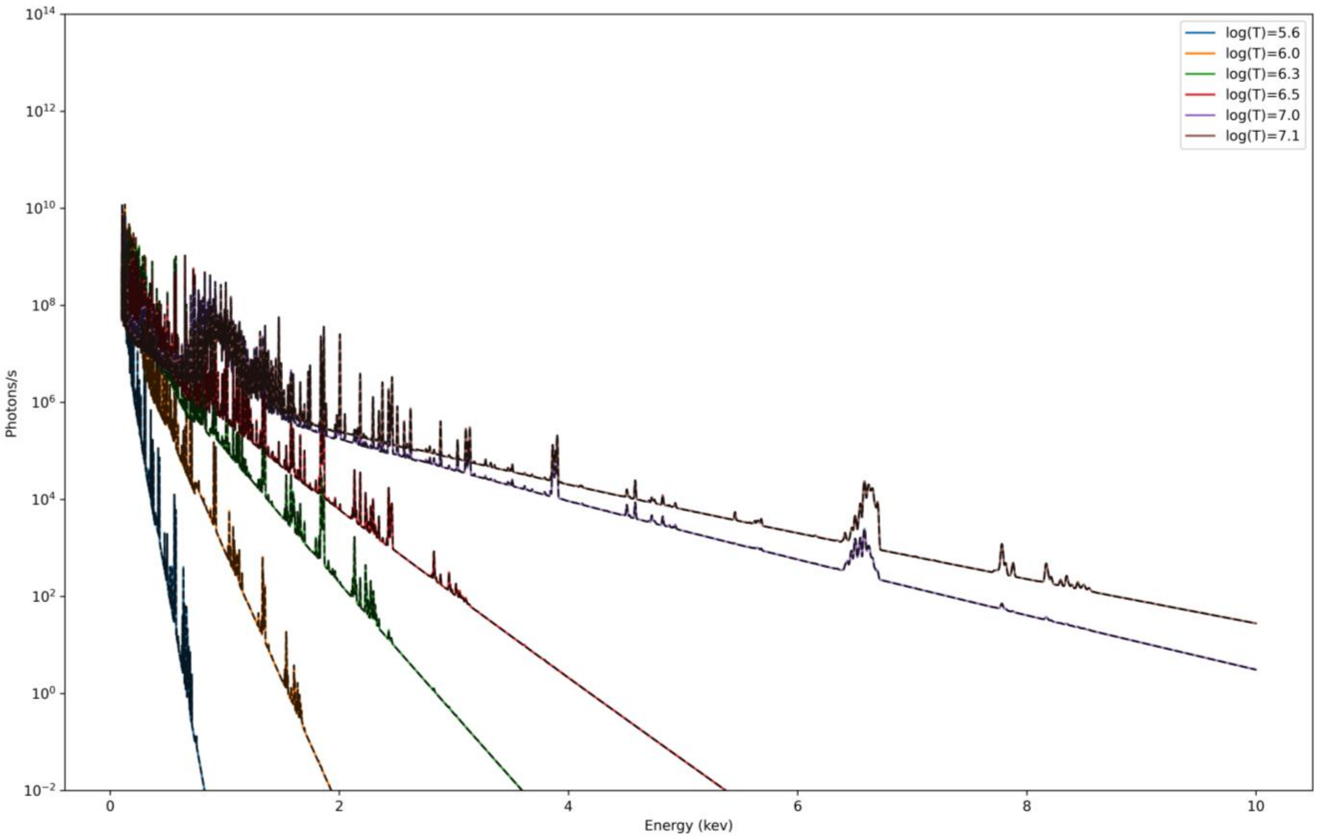
- Individual elemental spectra is calculated using CHIANTIpy in a grid of energies with dE=0.1 eV and log(Temperature) with dlog(T)= 0.001 and stored as lookup tables in netCDF4 format (electron density = 10^9 cm^{-3})
- For a particular log(T), the spectra for that element is obtained by linear interpolation between nearest log(T) gridpoints.
- Final spectra is obtained as weighted sum of individual interpolated elemental spectra, with weights as abundances and scaled by emission measure:

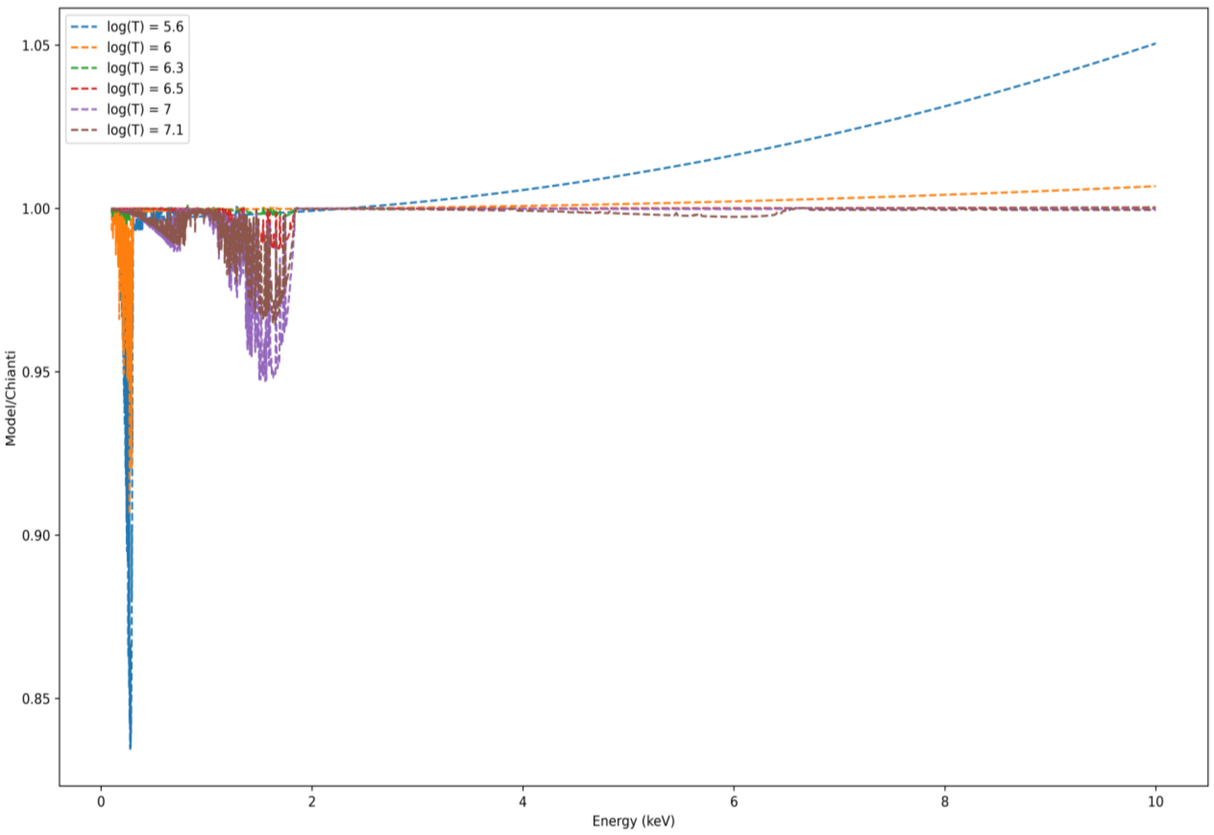
$$I(E) = EM * \sum_{i=1}^{30} X_i * I_i(\mathrm{E})$$

$X_i = N_i/N_H$, i = atomic number

EM = Emission Measure

Exact calculations vs Table based Model



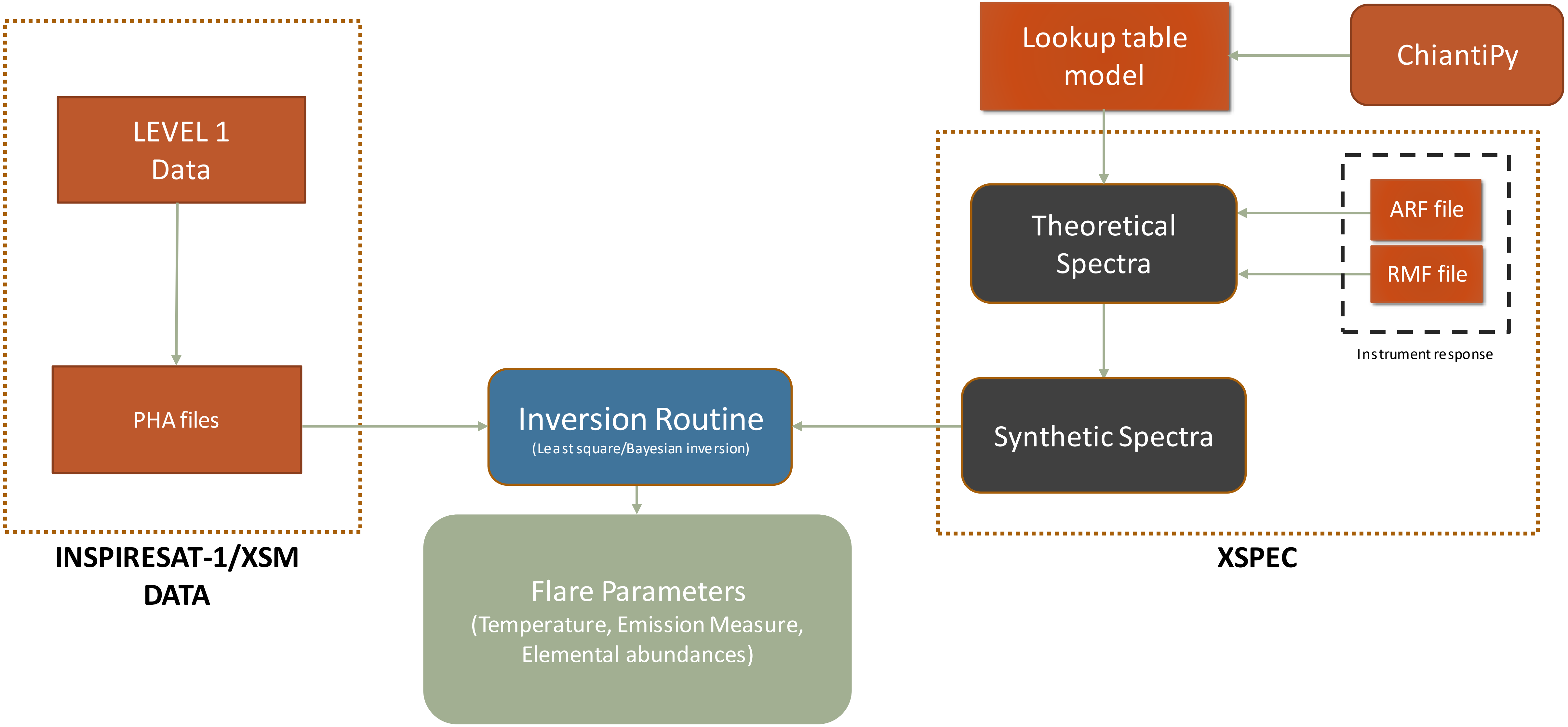


Exact calculation (using CHIANTIpy) in colors overplotted with model calculation (using table) in black for different log(Temperatures)

Ratio of model to exact calculations vs energy plotted for different log(Temperatures)

Methodology for retrieval of flare parameters

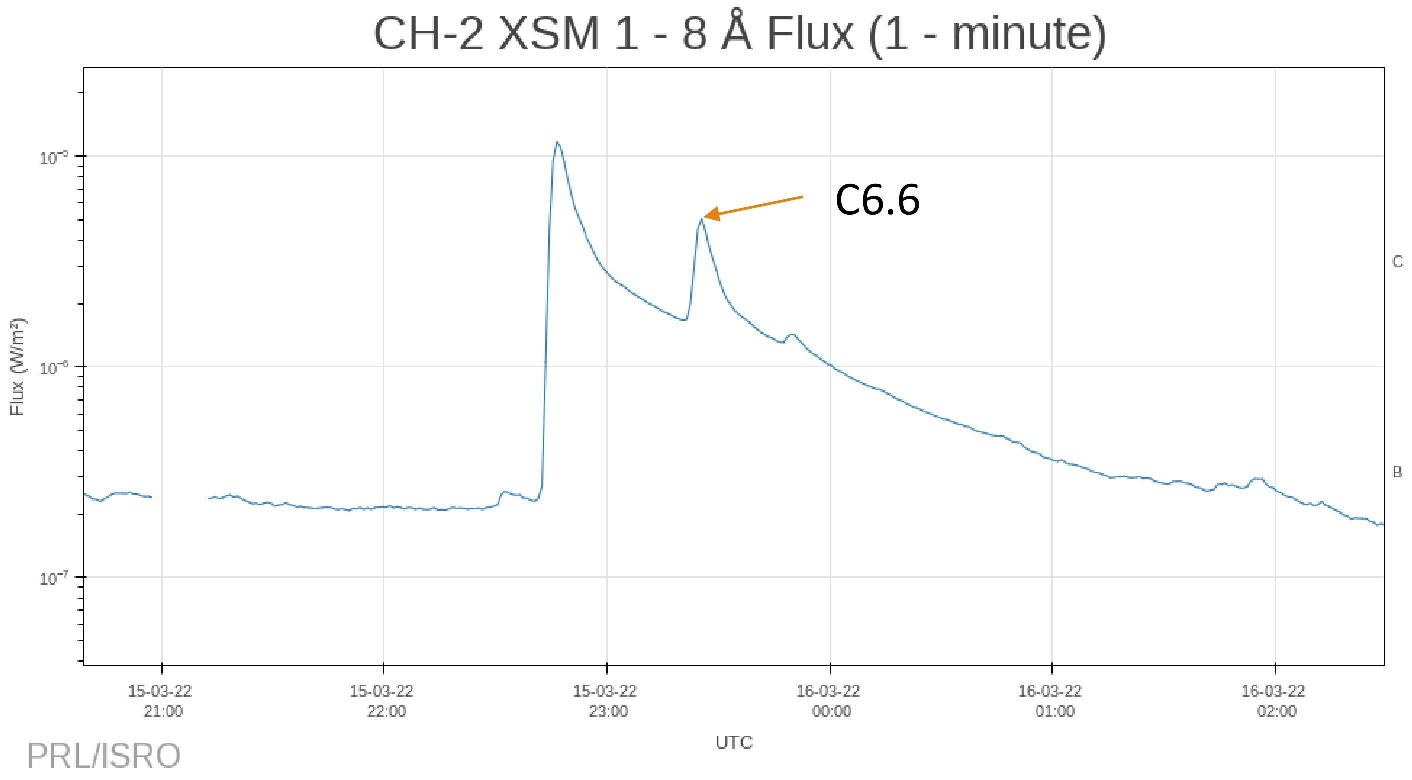
Overview of Methodology



Fitting using XSPEC

- The lookup tables are generated and model is added to (py)XSPEC (An X-Ray Spectral Fitting Package) (Arnaud, K.A., 1996).
- The parameters of the model are temperature (in MK), emission measure (in 10^{26} cm^{-5}) and Abundance Factors (AF) which are scaling factors with respect to Feldman extended coronal abundances (Feldman et. al, 1992).
- The data from the instrument are converted to *.pha* files and loaded to XSPEC.
- The instrument responses are loaded as corresponding *.rmf* and *.arf* files.
- First a preflare time interval is chosen and an averaged spectrum is fitted with single temperature isothermal model.
- Then the flare spectra is fitted with a two temperature Isothermal model (with the same abundances for both temperatures) + the preflare single temperature model.

Analysis

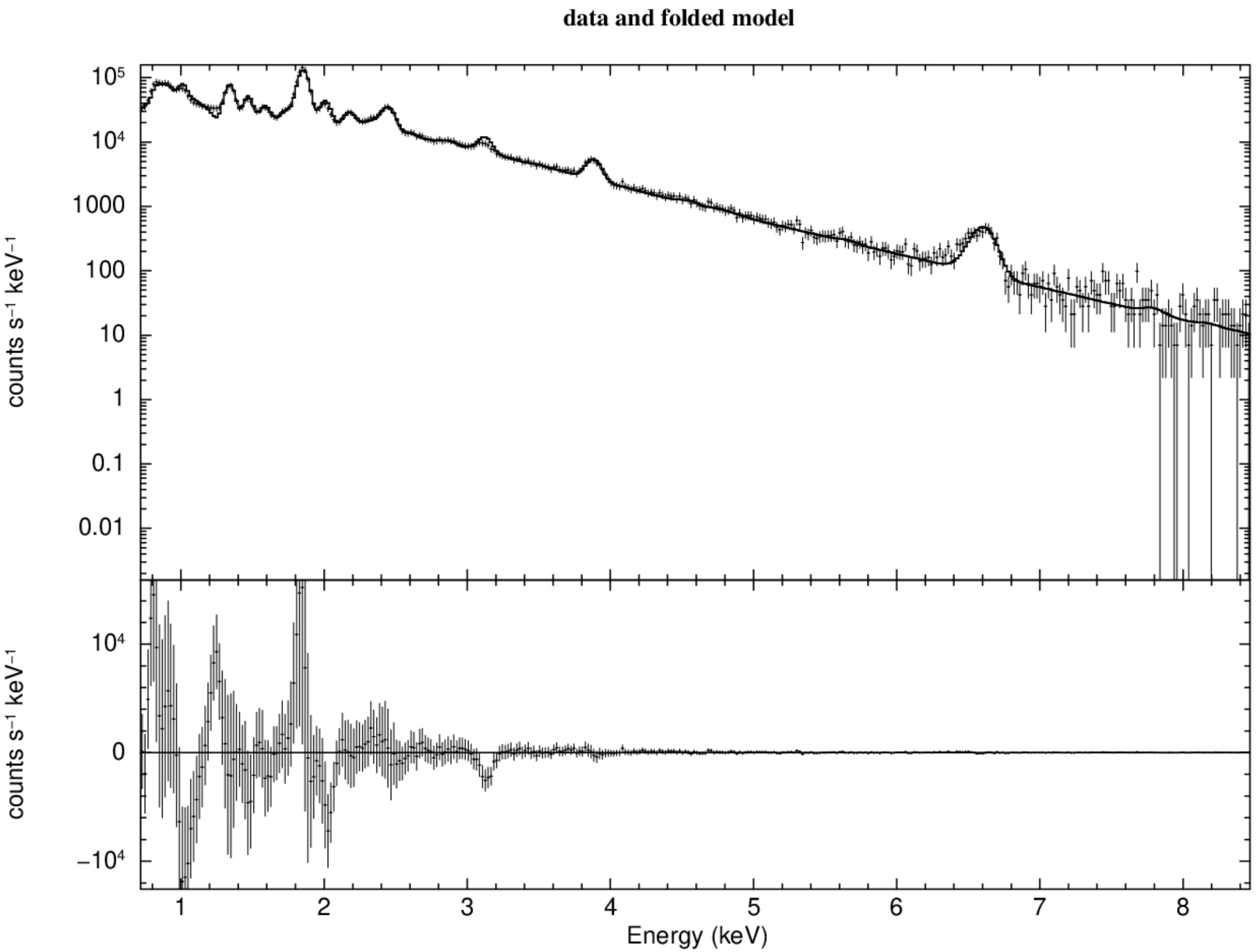


Credit: https://www.prl.res.in/ch2xsm/

Analysis of C6.6 Flare on 2022-03-15

- We analysed the flare that occurred on 2022-03-15 at peak approximately 23:25 using the above methodology.
- The flare was chosen because both XSM and DAXSS has observed the flare simultaneously and completely.

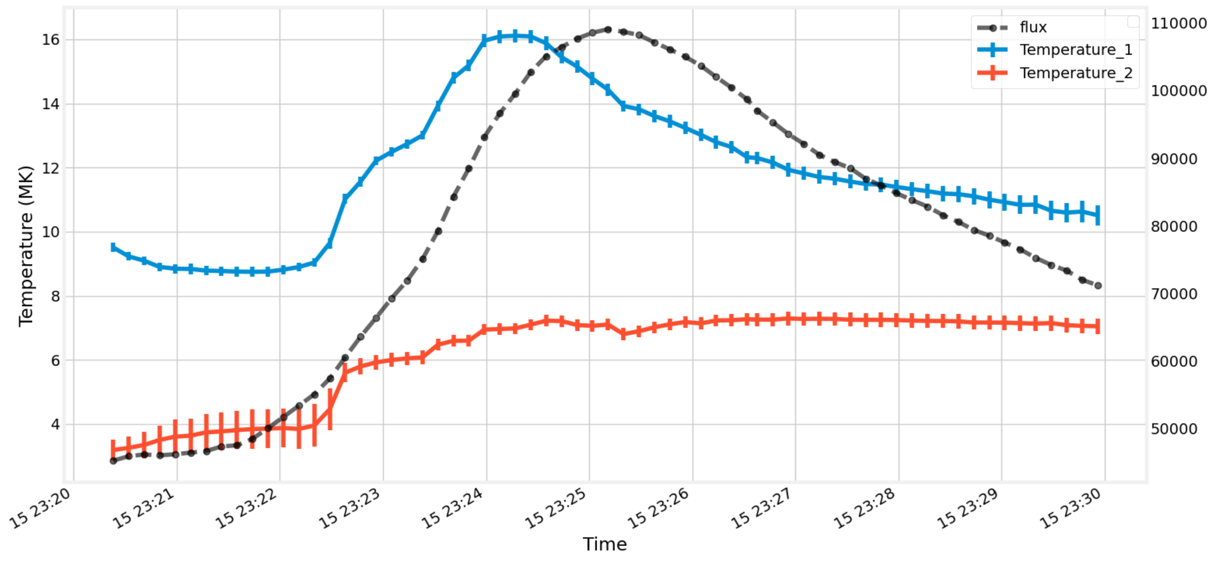
DAXSS Results:
Fitted spectrum

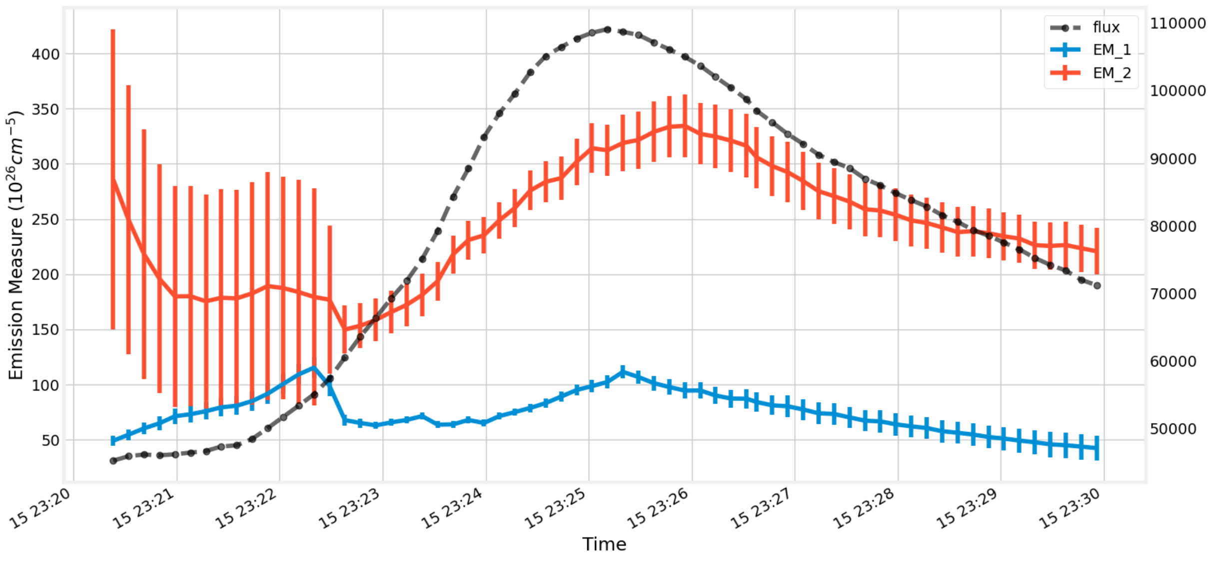


Spectrum data and fitted Model along with residuals at time 2022-03-15T23:26:47.

DAXSS Results:

Temperature and Emission measure



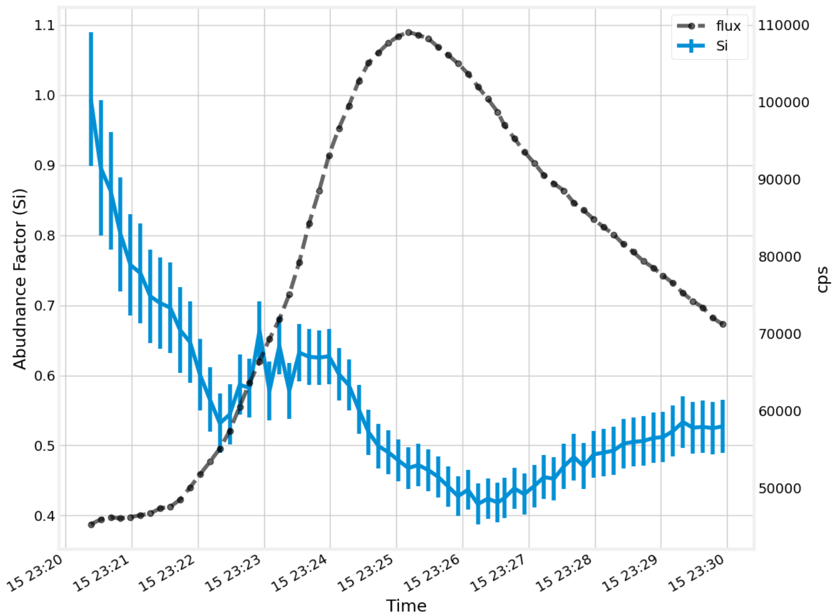


Temperature peaks before flux peaks while Emission measure peaks with the flux.

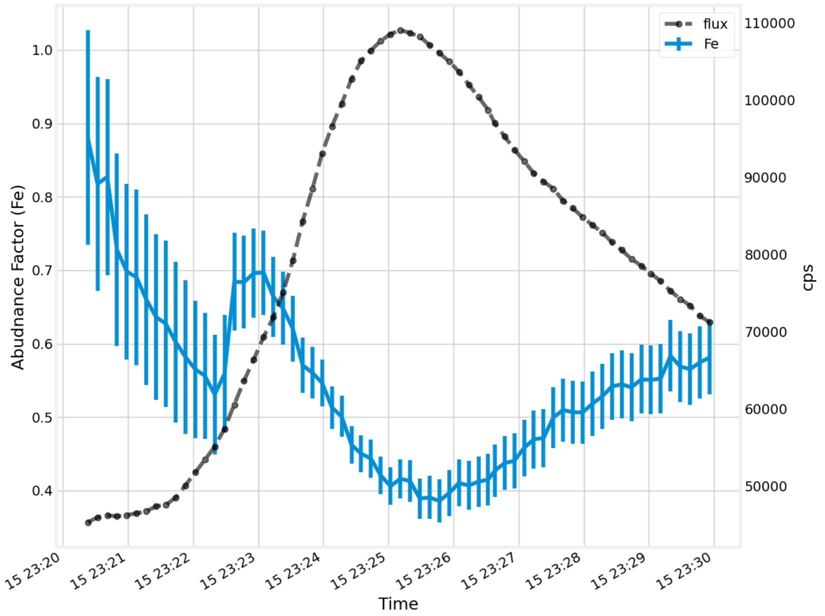
DAXSS Results:

Abundance factors

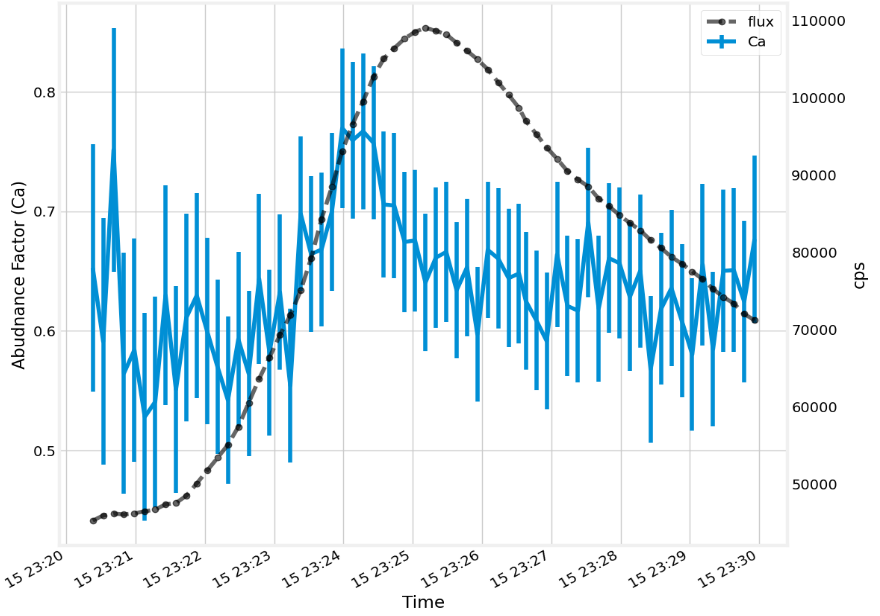
Factors seems to drop to photospheric values during the flare with some showing recovery.



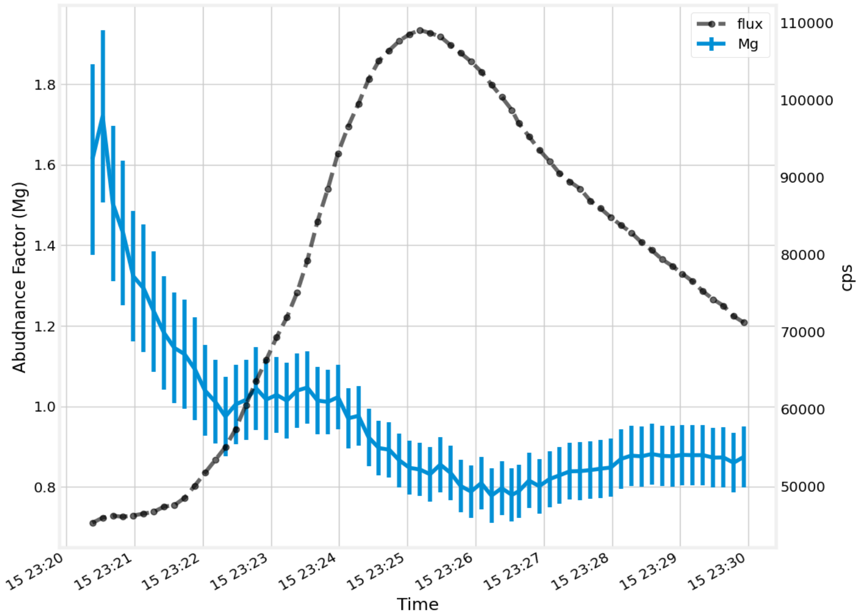
Si



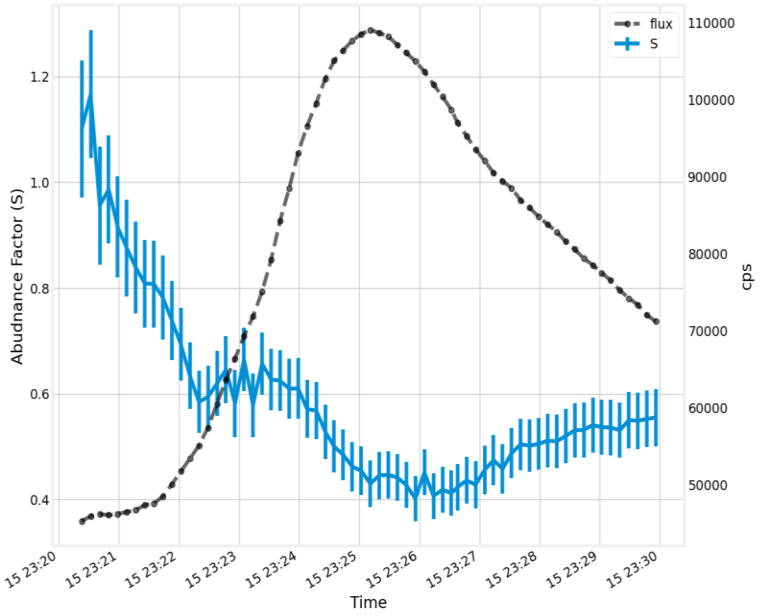
Fe



Ca



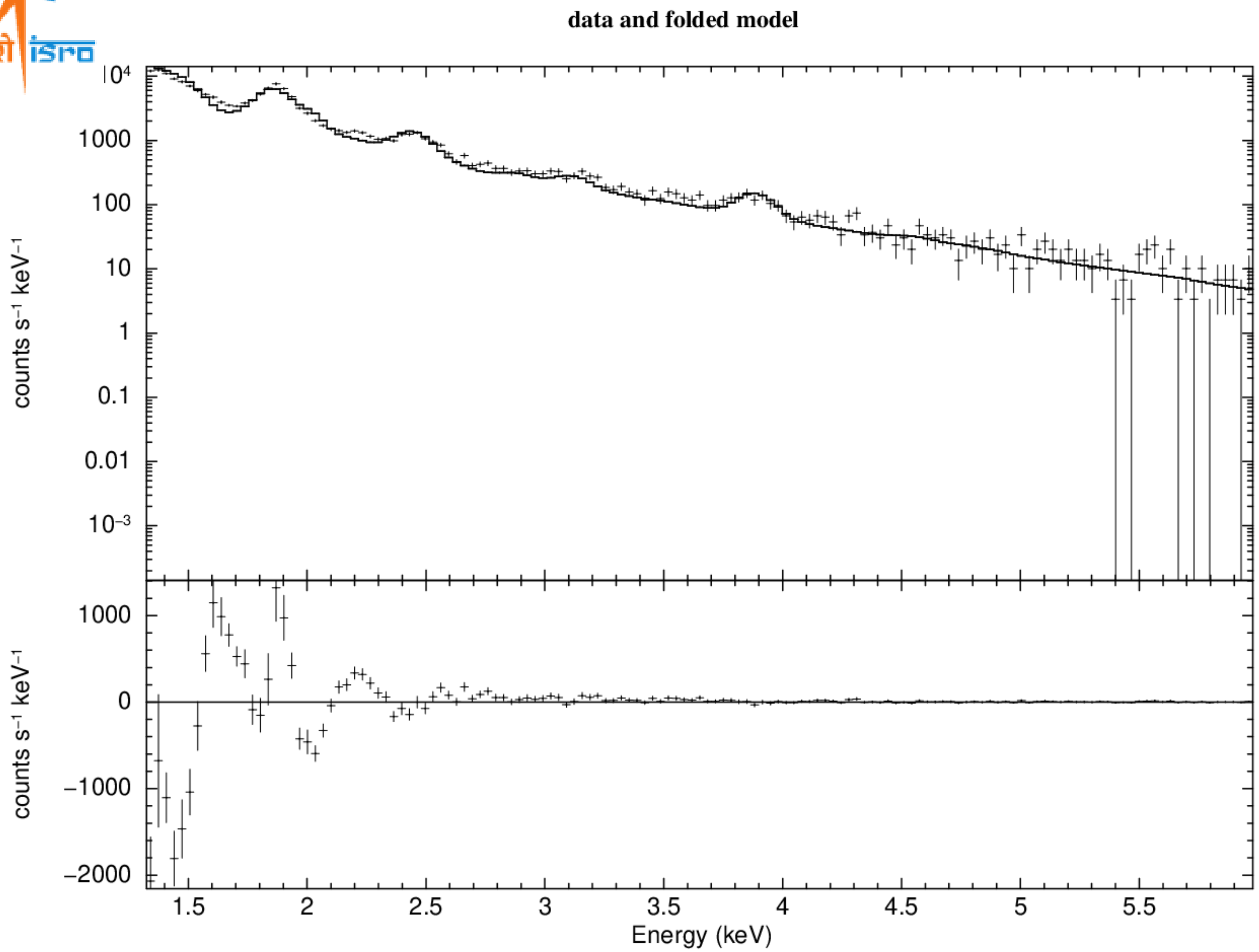
Mg



S

XSM Results:

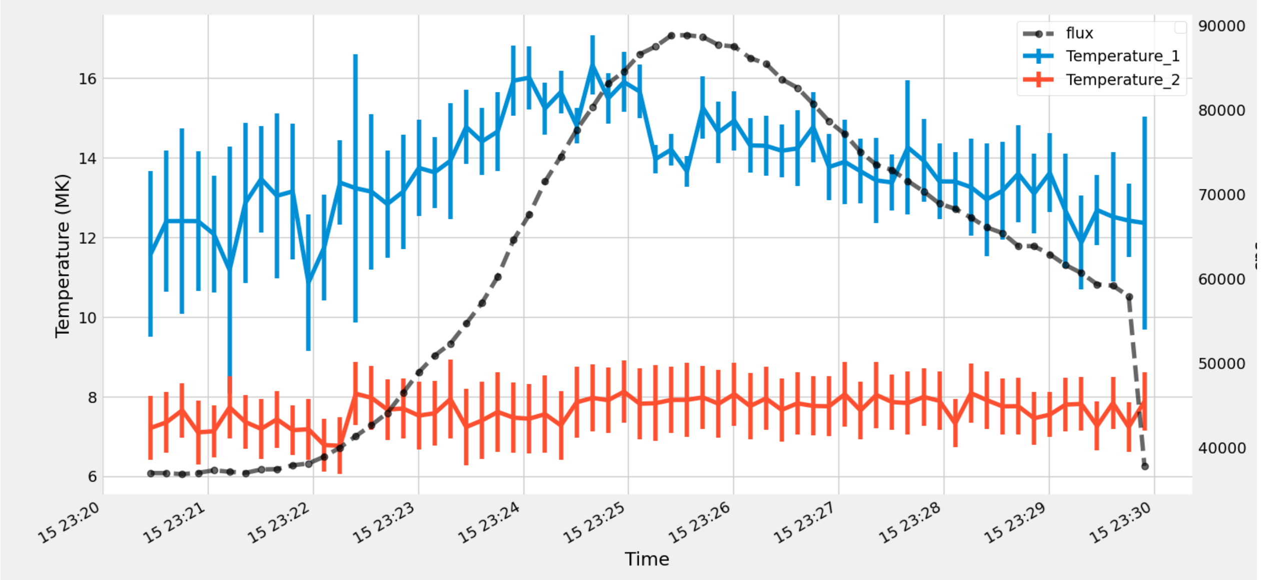
Fitted spectrum

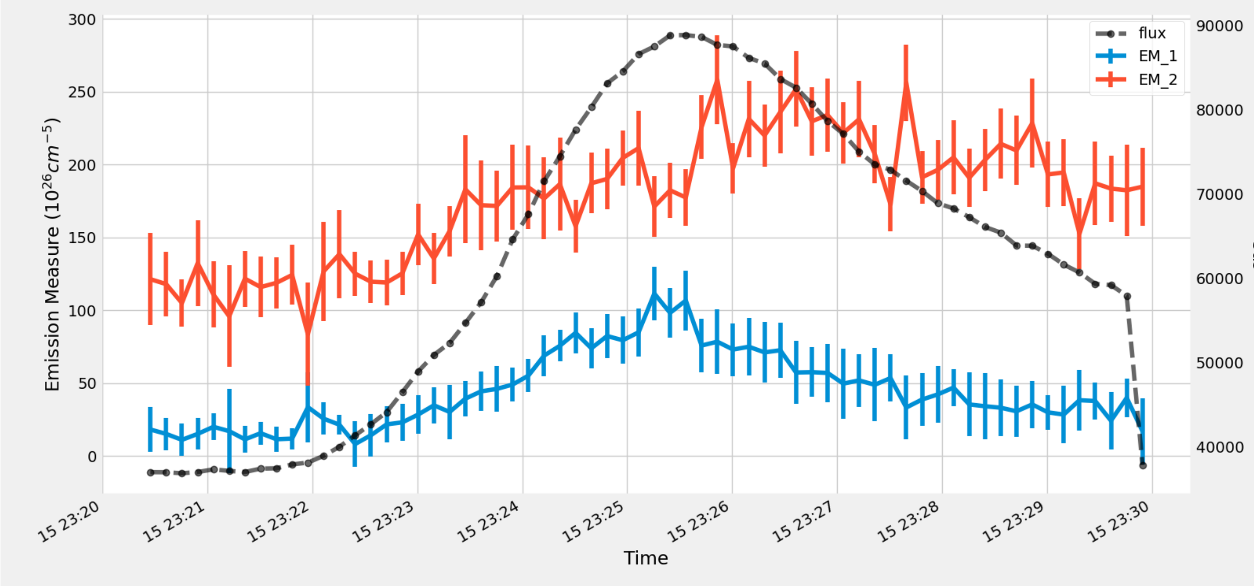


Spectrum Data and fitted Model along with residuals at time 2022-03-15T23:26:45.

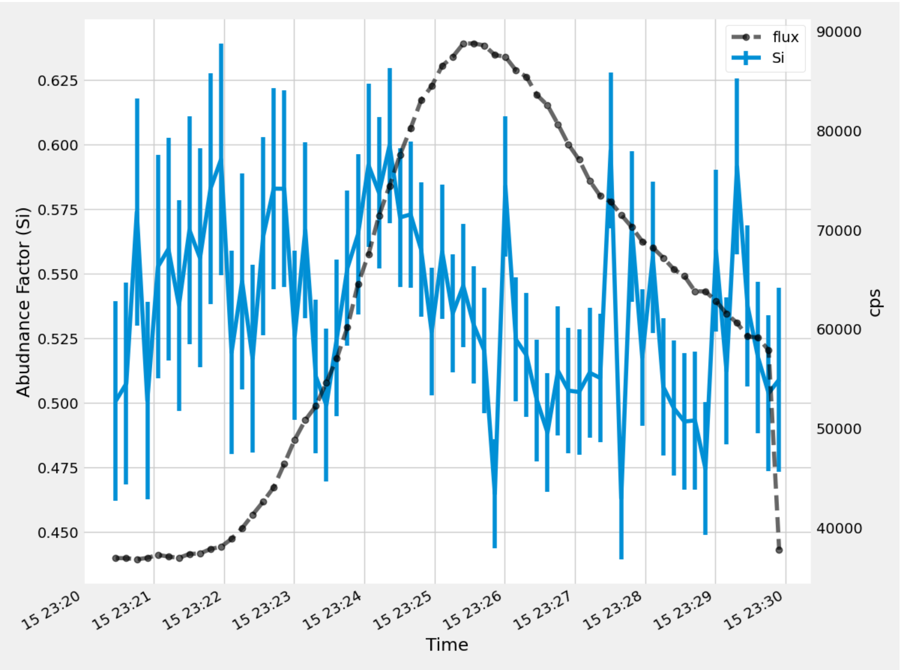
XSM Results:

Temperature and Emission measure





The Temperature peaks before flux peaks while Emission measure peaks with the flux, but not as clearly as in DAXSS data.

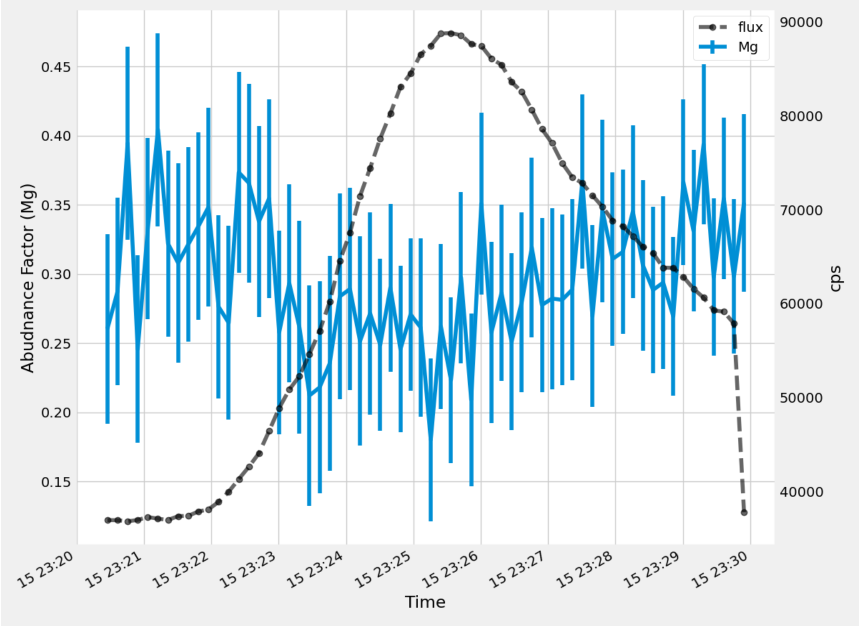


Si

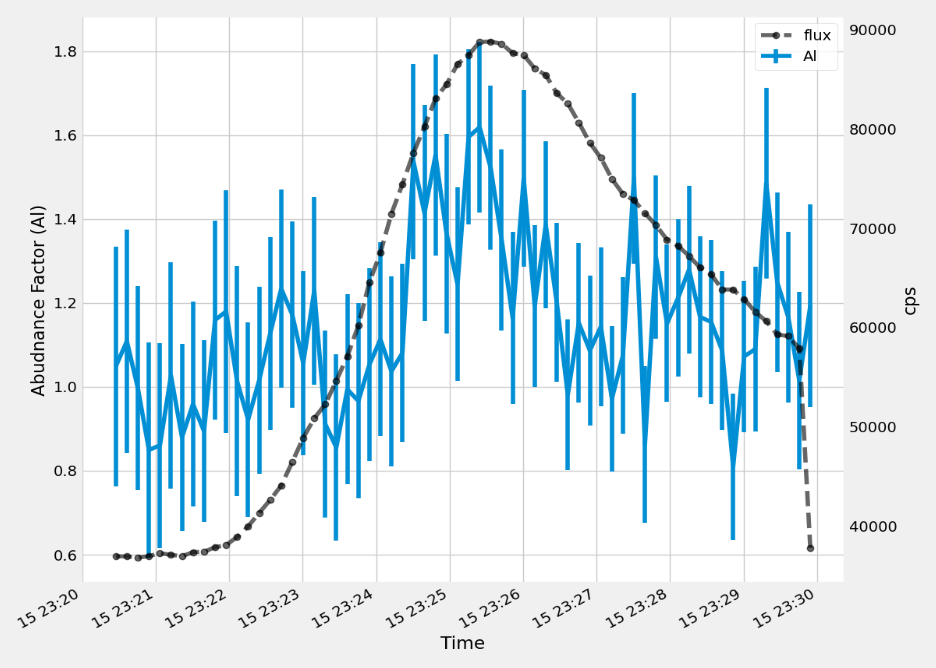
XSM Results:

Abundance factors

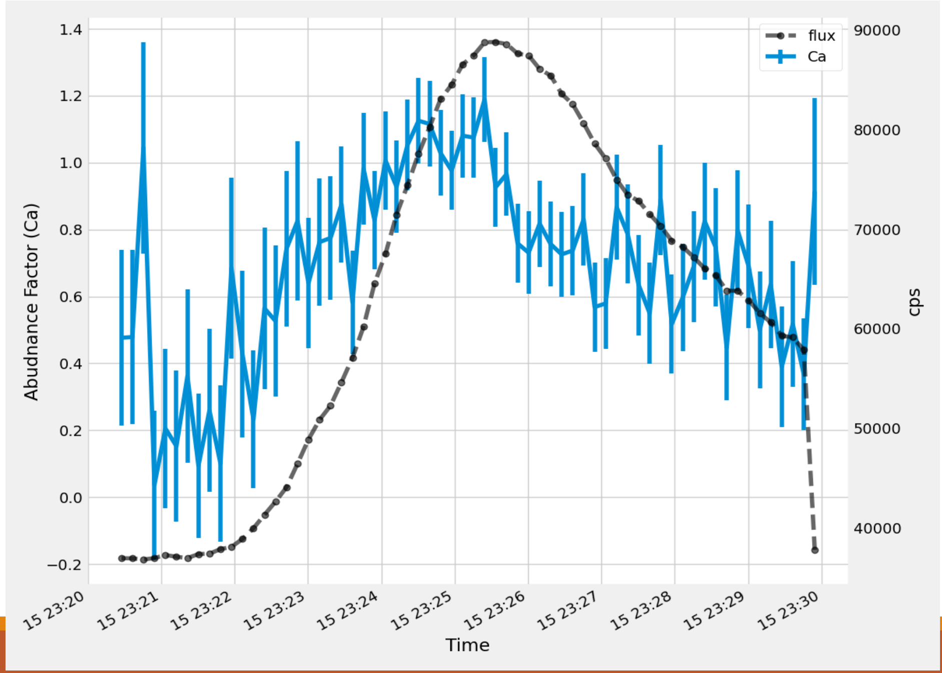
There is little or negligible evolution of elemental abundances observed within the error bars using the XSM observations.



Mg



Al



Ca

Summary

- We explored the temporal evolution of temperature, emission measure and elemental abundances during a flaring event using soft X-ray data from CH-2 XSM and IS-1 DAXSS.
- The DAXSS data show that Temperature peaks before the peak of the flux, emission measure peaks coincides with flux peak and elements tends to drop towards their photospheric values during the flare.
- These features are consistent with the standard flare models.
- XSM data also broadly show patterns in temperature and emission measure similar to the DAXSS data.
- Further investigation with more number of flares with complete and simultaneous observations from both the instruments is required to understand the trends observed in retrieved elemental abundances.

Acknowledgements

- We acknowledge the helpful discussions and suggestions that has been provided by DAXSS and XSM teams that was critical for the presented work.
- CHIANTI database and CHIANTIpy was used extensively throughout the work.

THANK YOU!