Getting the flare iron abundance from RHESSI observations of the Fe line feature in solar flares

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Solar Flare X-ray Spectrum 1—10 keV

Solar flares occur as a result of magnetic reconnection in the solar corona, giving rise to bursts of hard (>10 keV) X-ray and microwave radio radiation.

The aftermath is a **hot plasma (temp. around 20 x 10^6 K)** lasting minutes to hours, cooling by radiation and conduction down to the relatively cool chromosphere (temp. 10^4 K). This plasma emits soft X-rays in the range 1—10 keV.

Some of this radiation is in the form of **free—free and free—bound continua**, as high-energy electrons collide with target H ions; the remainder is due to intense **spectral lines** of abundant elements.

Spectral Lines: Observations with high-resolution and broad-band resolution detectors.

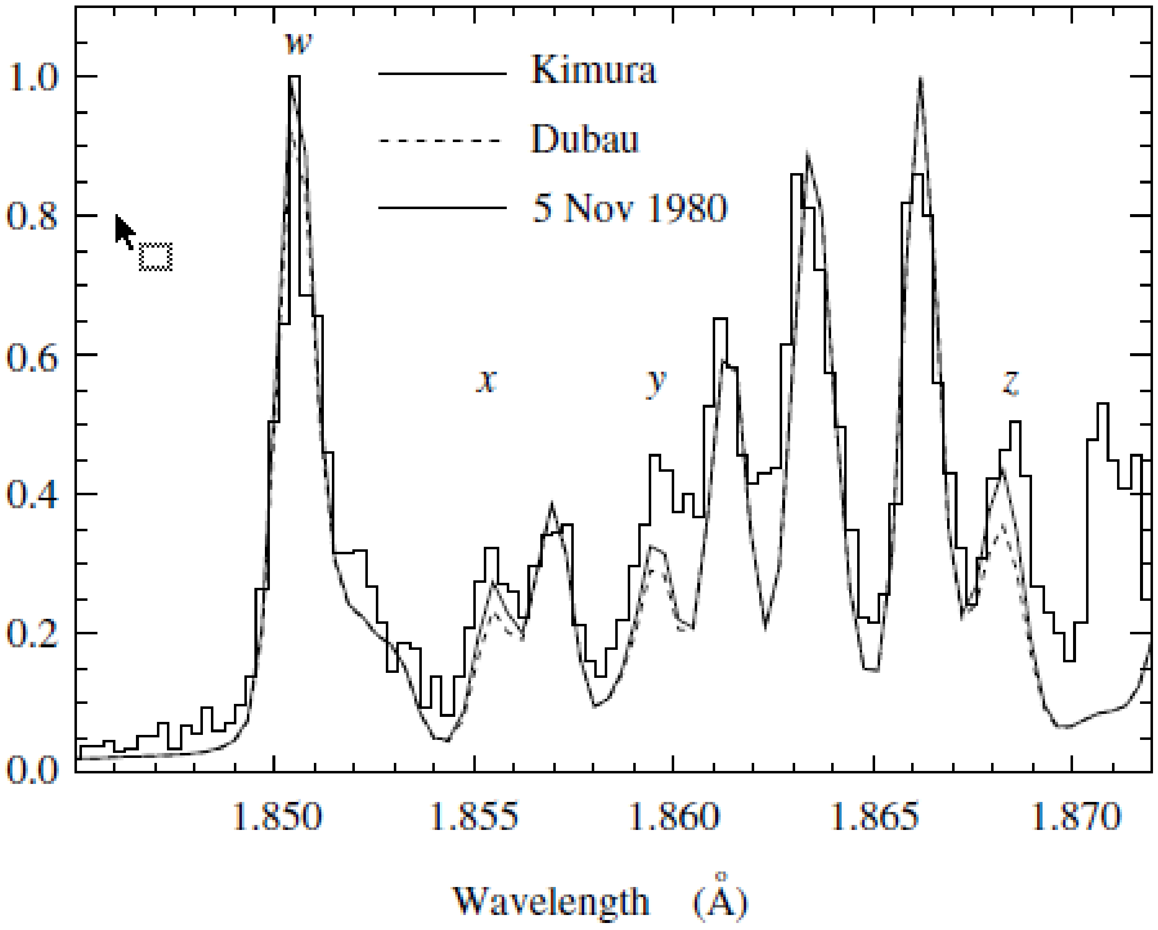
Spectral lines are emitted by ions of elements abundant in the corona – Ne, Mg, Al, Si, S, Ar, Ca, Fe.

These lines have been seen by **high-resolution instruments** – often crystal spectrometers like the FCS and BCS on Solar Maximum Mission (SMM) and RESIK. **Continuum sometimes difficult to determine** because of the fluorescence of the crystal material giving rise to a background emission.

The lines are also evident in spectra from **broad-band instruments**, e.g. the germanium detectors of ***RHESSI*** (operational from 2001). The spectral resolution of two of the nine detectors is ~ 1 keV at 6 keV (similar to STIX).

With Silicon PIN detectors as was used on the Chandrayaan spacecraft, **higher resolution** can be achieved (down to 100 eV at 6 keV).

Example BCS high-res. spectrum Fe XXV lines at 1.85Å

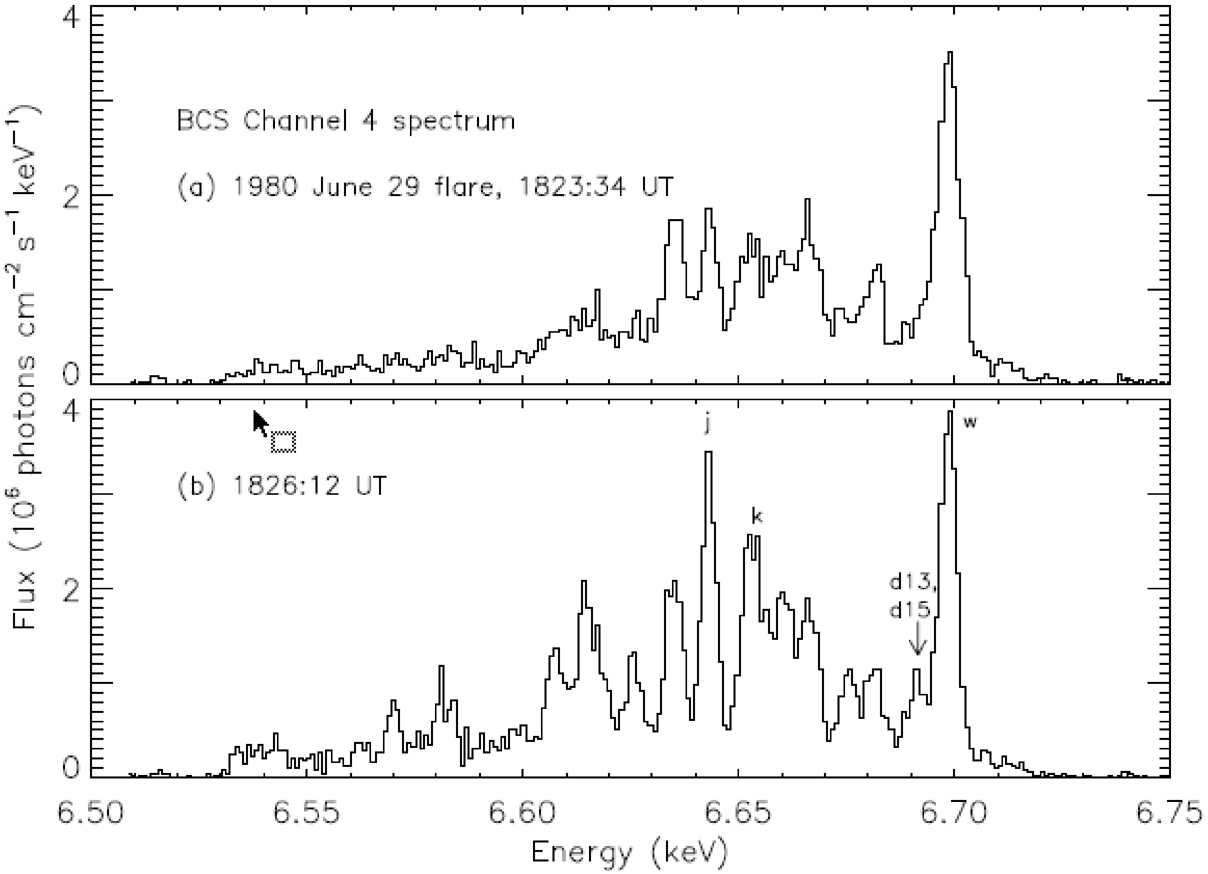


Histogram = observed solar flare spectrum (curves are model spectral fits).

Background here is not real continuum but due to crystal fluorescence.

Wavelength resolution approx. 0.001 Å.

BCS Flare Spectra plotted against Energy (keV)



Energy resolution is approx. 4 eV (corresponding to 0.001 Å).

Note energy to wavelength conversion is **λ (Å) = 12.4 / E (keV).**

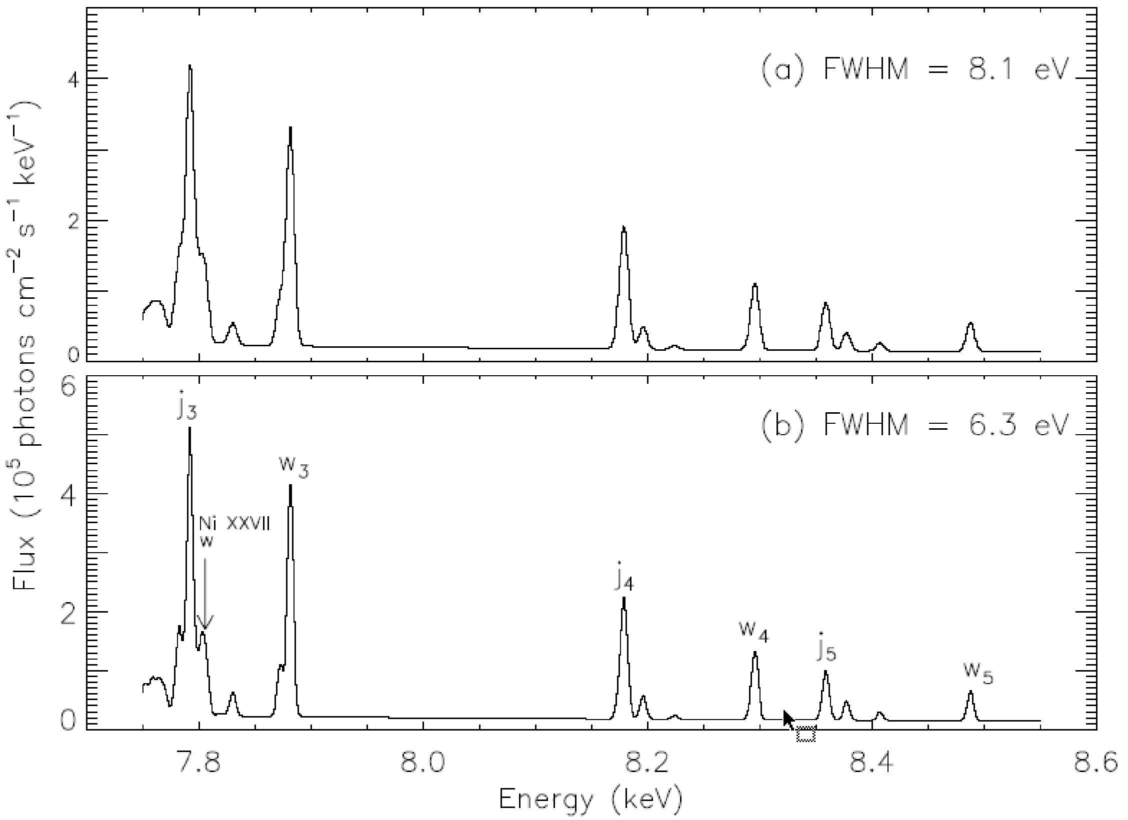
The Fe line complex at 6.7 keV (approx. 1.9 Å)

As observed with high resolution, there is a complex of lines at 1.9 Å (**6.7 keV**) due to **highly ionized iron atoms** ("resonance" line *w* of helium-like Fe (Fe XXV) and numerous "satellite lines"). At broad-band resolution (e.g. RHESSI) this is seen as a **single broad feature** on top of a continuum.

The lines are emitted at temperatures *T* of at least 15 x 10^6 K (=15 MK). Calculations from atomic codes (e.g. CHIANTI) give line irradiances (fluxes) and wavelengths (or photon energies). CHIANTI also gives continuum irradiances (free—free and free—bound) as functions of T and energy.

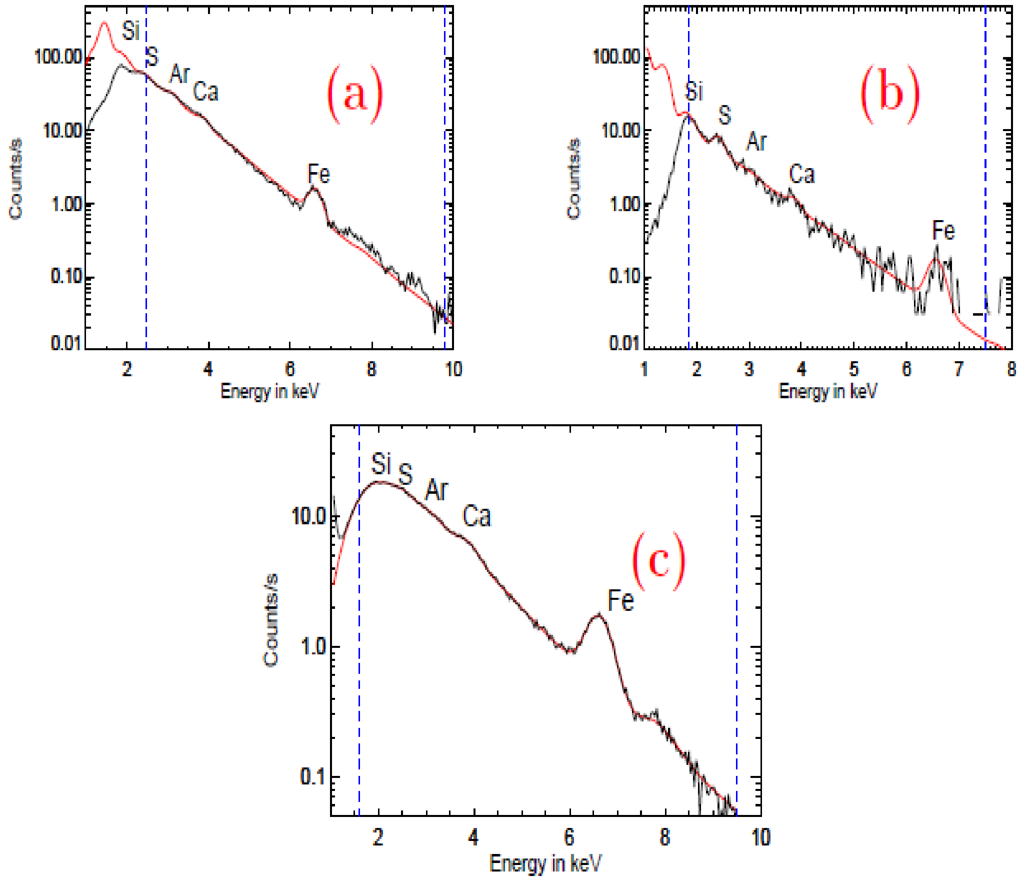
With broad-band resolution there is also a feature due to several Fe lines plus minor contribution due to Ni lines at **8 keV**.

Fe line feature at approx. 8 keV



CHIANTI simulation of the 8 keV region – temp. = 20MK with energy resolution = 8.1 and 6.3 eV.
Region contains **Fe XXV lines** (w3 to w5) with satellites in the 7.7 to 8.5 keV region – never been seen at high resolution. There is a **< 10% contribution due to Ni XXVII lines** so the 8 keV feature mostly due to Fe.

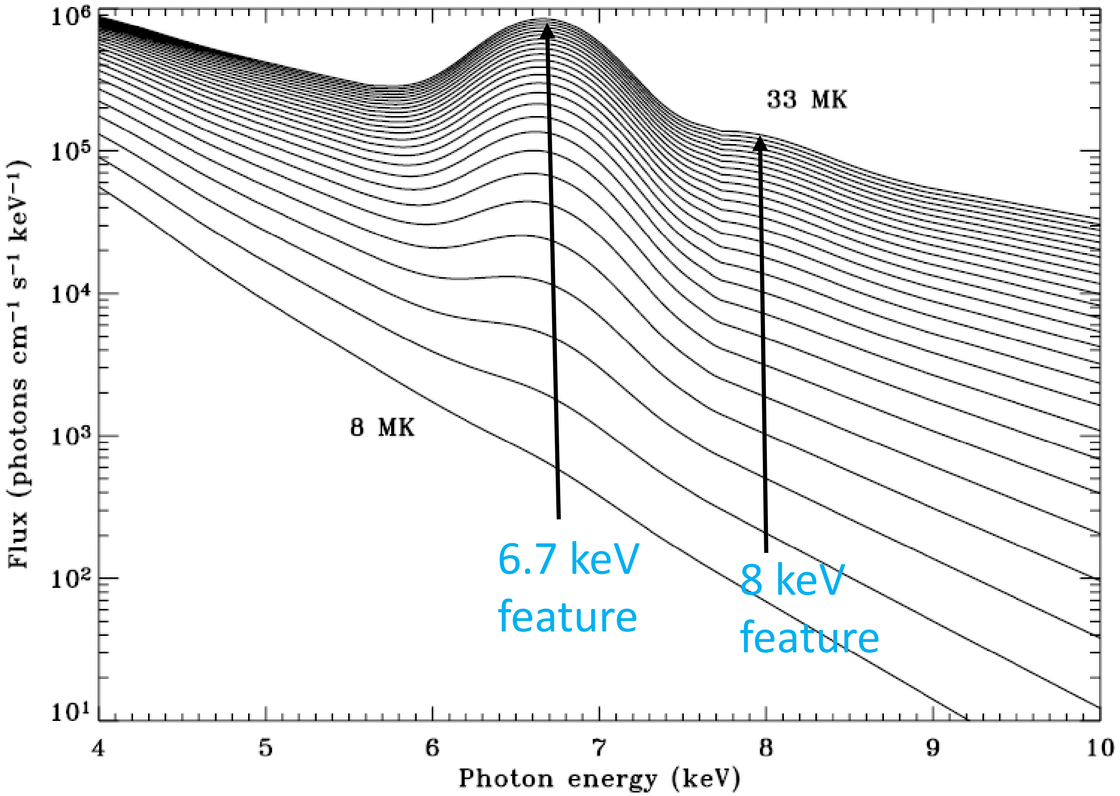
Example broad-band flare spectra



Spectral res. approx. 180 eV (at 6 keV) for Chandrayaan-1 XSM (b) spectrum.
The 8 keV feature is evident for spectra (a) and (c).
The background for all these spectra (a to c) is continuum, not instrumental.

Solar Flare spectra from (a) *SMART-1* (26-6-2004); (b) *Chandrayaan-1 XSM* (5-7-2009); (c) *MESSENGER SAX* (2-1-2014). From Narendraneth et al. (2020, Solar Phys.)

Examples of model solar flare spectra from CHIANTI for RHESSI spectral resolution (1 keV).



Model (CHIANTI) spectra for a solar flare plasma with vol. emission measure 10^{48} cm^{-3} solar coronal abundances with T = 8 to 33 MK. The y-axis is spectral irradiance (flux) in photons cm^{-2} s^{-1} keV^{-1}.

The RHESSI imaging-spectrometer

RHESSI was launched in Feb. 2001, near the peak of the solar cycle, so saw numerous very intense flares. After over twenty years of operations, *RHESSI* entered the Earth's atmosphere in April 2023.

Nine cooled germanium detectors sensed incoming photons from solar flares, with the top-most 1cm sensitive to soft X-rays.

The full spectral range was 3 keV to 17 MeV, with energy resolution down to 1 keV for smaller energies (of interest here).

Spatial information was achieved with modulation grids with the spacecraft rotating once/2 seconds. The spatial resolution was from 2 arcsecs to 36 arcsecs depending on energy.

To avoid saturation, attenuators were inserted over the detectors at times of high activity – A1 state (thin attenuator) and A3 (thick + thin attenuators), with A0 state (zero attenuator).

Analysis of *RHESSI* flare spectra

In two works (Phillips et al. 2006 and Phillips & Dennis 2012) we analyzed flare low-energy spectra including the 6.7 keV Fe line feature and 8 keV Fe/Ni feature, with thermal continuum (covering the 3 keV to 12 keV range). The time resolution was 2 s.

We selected spectra in the **slow decay of flares** when available to avoid the complication of multi-thermal plasmas.

Most of the spectra were from detector 4 (of the 9) which had the best spectral resolution and the best coverage of low energies (<10 keV).

Spectra with the **A1 attenuator** usually gave the best fits but A0 spectra were used for low-intensity time intervals.

Account of various instrumental effects – the finite spectral resolution, K-escape events, pulse pile-up – is taken into account through the sophisticated software package called OSPEX (mostly written by Dr Richard Schwartz at GSFC).

Analyzing RHESSI data for the solar flare Fe abundance

In our 2006 paper we used OSPEX with the MEKAL (Rolf Mewe et al.) theoretical X-ray spectra including formulas for free—free and free-bound continua.

At my instigation, Dr Schwarz used the CHIANTI theoretical spectra with solar abundances selected by the user. For our 2012 paper we used CHIANTI v. 6. The chief differences from MEKAL are for the 8 keV feature and (maybe) the continuum.

The free—bound continuum calculation needs an abundance set – we used Feldman (1992) "coronal" values, including the abundance of Fe.

(A slight danger of a circular argument! we are determining A(Fe) from *RHESSI* spectra. However, Fe is only a minor contributor to the continuum.)

Using OSPEX for typical RHESSI spectrum

Black histogram = **observed spectrum during the decay of an X1 flare** on 2003 Oct. 23 with A1 attenuator.

Spectral fit over range 5.5—33 keV with the following:

- **Thermal part** assumed isothermal (**green**) from CHIANTI (lines + contm).

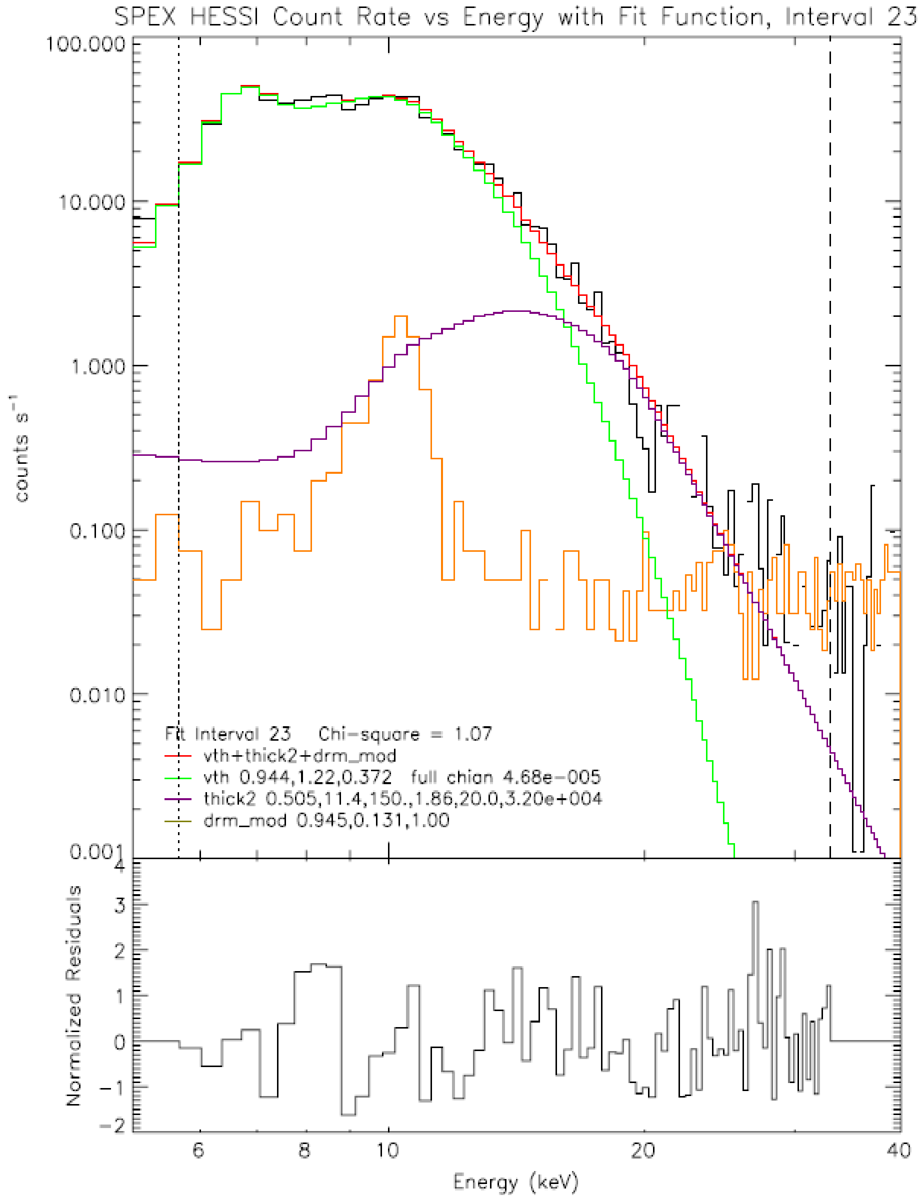
- **Nonthermal part** to fit energies > 20 keV (**purple**).

- Spectrum accounts for **instrumental effects**, e.g. line at 10 keV due to Ge Kα (**gold**).

Note that **background** (non-solar) emission from night-time spectra already **subtracted**.

For this spectrum, there were 8 free parameters *T*, EM, *F* (= factor adjusting Fe abund. from Feldman (1992) set), and nonthermal sp. parameters.

All spectral components were folded through the det. 4 **detector response function DRM**, adjusting all or some of the free parameters to get a good enough fit as estimated by χ^2



Getting the Fe abundance from F factors

F = factor from OSPEX fit to RHESSI det. 4 spectra that multiplies the Fe abundance in Feldman (1992).

Following conventions we express the Fe abundance **A(Fe)** logarithmically with respect to hydrogen H:

$$A(Fe) = 12. - \log(N[Fe]/N[H])$$

For **photospheric Fe abundance**, **A(Fe) = 7.50** ± 0.04 (Asplund 2009).

Feldman (1992) gives **A(Fe) = 8.10** (**flares**, coronal sources).

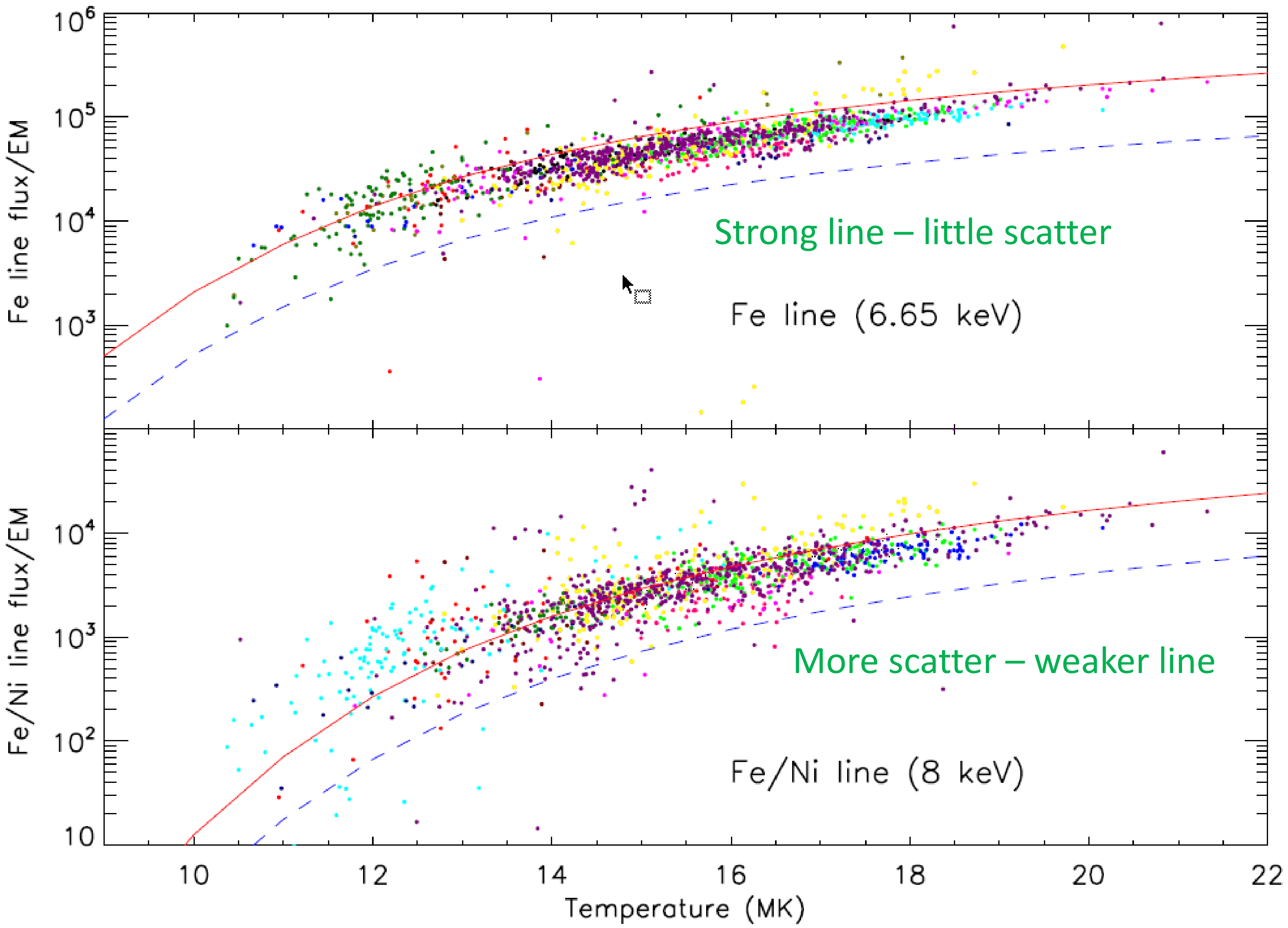
So *F* = the factor multiplying Feldman's abundance A(Fe) corresponding to $N[Fe]/N[H] = 1.26 \times 10^{-4}$

Plots of Fe and 8 keV features per unit EM against *T*(MK).

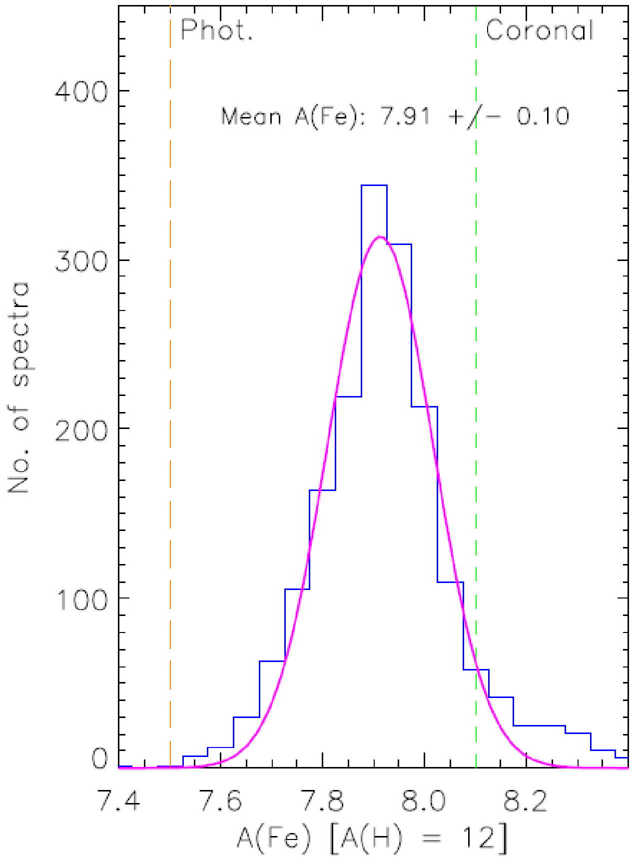
Time intervals within 20 RHESSI flares indicated by different coloured dots.

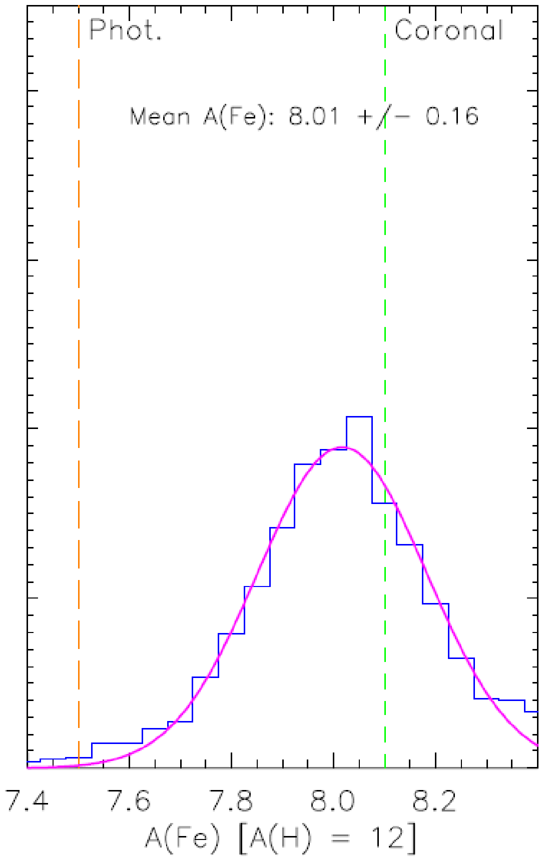
Red curve is the dependence of each line feature on *T* for Feldman (1992) abundances.

Blue dashed curve is for photospheric abundances.



Distribution of A(Fe) values using RHESSI flare spectra





Fe line feature 6.7 keV **Fe/Ni line feature 8 keV**

Conclusion: Flare Fe abundance from Phillips & Dennis (2012)

From analysis of the 6.7 keV line feature, we derived

A(Fe) = 7.91 ± 0.10 (s.d.).

For the 8 keV line feature, we derived **A(Fe) = 8.01 ± 0.16**.

There is thus a 23% difference, but with the standard deviations this is almost compatible.

Nevertheless, the plots show that there is evidence for the 8 keV feature giving a **consistently higher Fe abundance**.

The reason may be an instrumental line of W (tungsten) in the thin attenuator not sufficiently allowed for in the OSPEX software.

Other measurements from flare X-ray spectra

Mercury *MESSENGER* SAX (Dennis et al. 2015) gave A(Fe) = **7.71 ± 0.07**. Isothermal and 2-T models for the emission – this result is for the isothermal case. Spectral res. 600 eV at 6 keV. Significantly less than this analysis. Hmm…

Chandrayaan-1 XSM (Narendranath et al. 2020) gave **7.99 ± 0.09**. Large spectral range, several elements. Isothermal and 2-T models for the emission. Spectral res. 860 eV at 6 keV.

Chandrayaan-2 XSM (Mondal et al. 2021) and Suzaku XIS (Katsuda et al. 2020) giant flares do not give the Fe abundance from their spectra.

Some conclusions and hints for STIX flare data analysis

Despite the relatively low spectral resolution (1 keV) of RHESSI flare spectra and the rather difficult analysis procedure, Fe abundance A(Fe) measurements are possible with an accuracy of 0.1 in the log.

We obtained, from **1898 spectra** during **20 RHESSI flares in 2002—2005**, **A(Fe) = 7.91 ± 0.10** from the Fe line at 6.7 keV and **A(Fe) = 8.01 ± 0.16** from the much weaker Fe/Ni (8 keV) feature.

These two results are just about compatible but the slightly higher value for the 8 keV line feature may be due to an underestimated instrumental line emission.

These values are similar to the Chandrayaan-1 XSM values but are more than the Messenger SAX value for a reason I can't explain.