Solar Flare Element Abundances and consequences for coronal modelling

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Overview

Over the past 7 years or so, the SRC group led by Janusz Sylwester have been analyzing X-ray spectra from RESIK, a crystal spectrometer on *CORONAS-F*.

RESIK operated 2001-2003 and obtained many 1000s of spectra in the 3.4-6.05Å during flares and from non-flaring active regions.

Our main concern has been element abundances but we have also looked at spectral line ratios and the X-ray continuum.

There is still work to do on the spectra, but we can now begin to look at patterns in our abundance findings and compare with theory – this is the subject of this talk.

Solar photospheric element abundances

Determinations of solar photospheric abundances have been greatly improved in recent years:

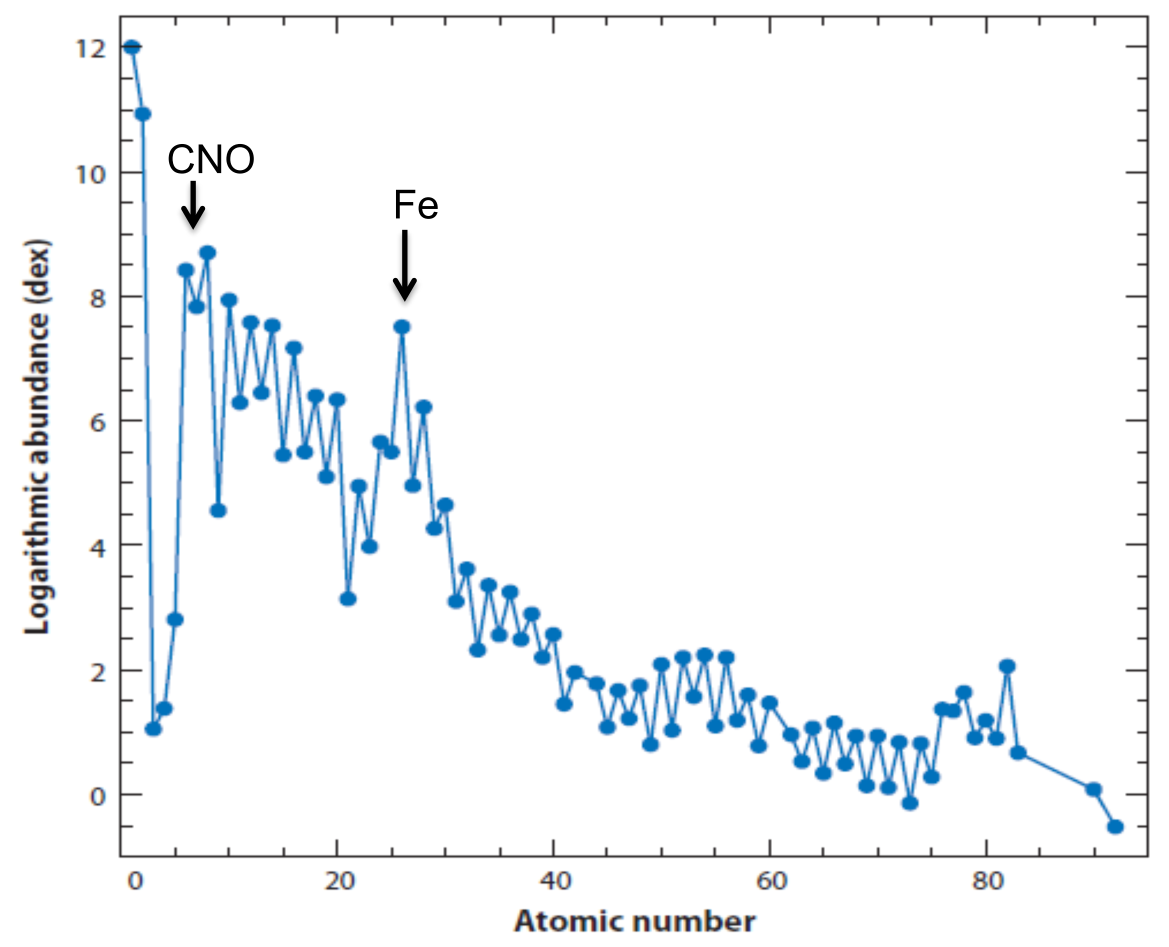
1) Improved observational data for absorption lines in the Sun’s visible spectrum;

2) improved atomic data describing absorption lines.

The abundance work of Grevesse & colleagues (1998) indicated near-perfect agreement with that expected from helioseismology.

But work by Asplund et al. (2009) and Caffau et al. (2011) indicates that the C, N, O abundances were too high by 23-38%; the new abundances result in a slight disagreement with helioseismology.

Solar photospheric abundances of all elements with Z (atomic number)



Some elements were made in the Big Bang "fireball" (H, He...), other elements (C,N,O...Fe...) were made in massive stars that underwent red giant or supernova phases.

From Asplund et al. (2009), ARAA, 47, 481

How abundances are expressed

As abundances vary widely (many orders of magnitude), we express abundances on a logarithmic scale, with H = 12.

So $A(\mathrm{El}) = 12.0 + \log_{10} (N_{\mathrm{El}}/N_{\mathrm{H}})$.

Typical photospheric abundances from Asplund *et al*.:

C	8.43
O	8.69
S	7.12
Ar	6.40
Fe	7.50

Element abundances in solar energetic particles (SEPs) and the corona

Early work by Pottasch (1964) and Veck & Parkinson (1981) suggested coronal abundances might be different from photospheric.

Later work by Meyer (1982), Feldman and colleagues (1992, 2000) showed that any differences between photospheric and coronal/SEP abundances could be explained by a dependence on the element's first ionization potential (FIP).

For "low-FIP" elements, the element abundance is enhanced in the corona by factors of up to 4.

For "high-FIP" elements, the photospheric & coronal element abundances are approximately equal.

The FIP effect

The dependence of abundances on the value of FIP is called the “FIP Effect”.

Possible Mechanisms:

Magnetic fields associated with emerging active regions bring ions of low-FIP elements up into the corona but not the neutral atoms of high-FIP elements (Vauclair).

A ponderomotive force F_p associated with Alfvén waves passing into coronal loops from chromosphere, tends to drive ions upwards (or even downwards: an inverse FIP effect).

Estimating coronal abundances

As with photospheric abundances, we need:

1) an accurate temperature model of the emitting region;

2) accurate atomic physics calculations (or experimental results), e.g. ion fractions and excitation rates (Maxwellian averages of cross sections).

Generally, we use *G(T)* = the contribution function for an emission line or continuum at a particular wavelength/energy (sometimes called the line's emissivity).

RESIK

Over the past few years, we have started a successful programme to estimate element abundances in flare and active-region plasmas using RESIK on *CORONAS-F*.

In its operational lifetime (2001-2003), RESIK had important advantages over previous spectrometers:

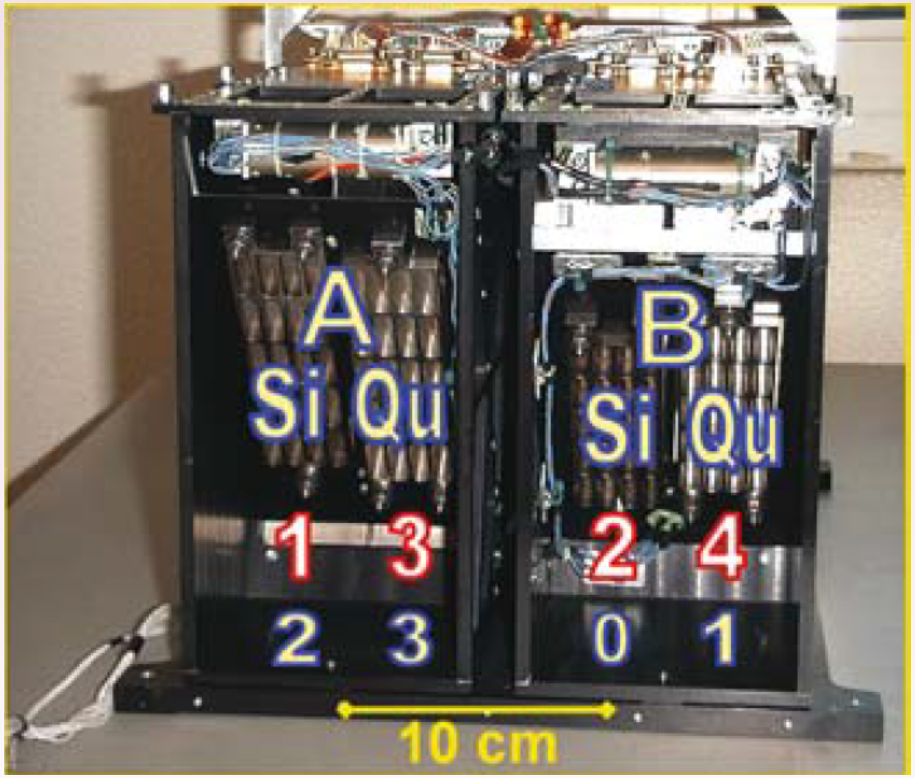
(a) very well calibrated through up-to-date crystal reflectivities (Sylwester et al. 2005);

(b) low fluorescence background so solar continuum was observed.

(c) very good for estimating element abundances including the very low FIP element K.

The RESIK instrument

The RESIK crystal spectrometer viewed the solar X-ray spectrum 3.4-6.05Å on *CORONAS-F*. It was operational 2001-2003, near maximum activity on the Sun, so observed many large flares.



RESIK observations in 2001-2003

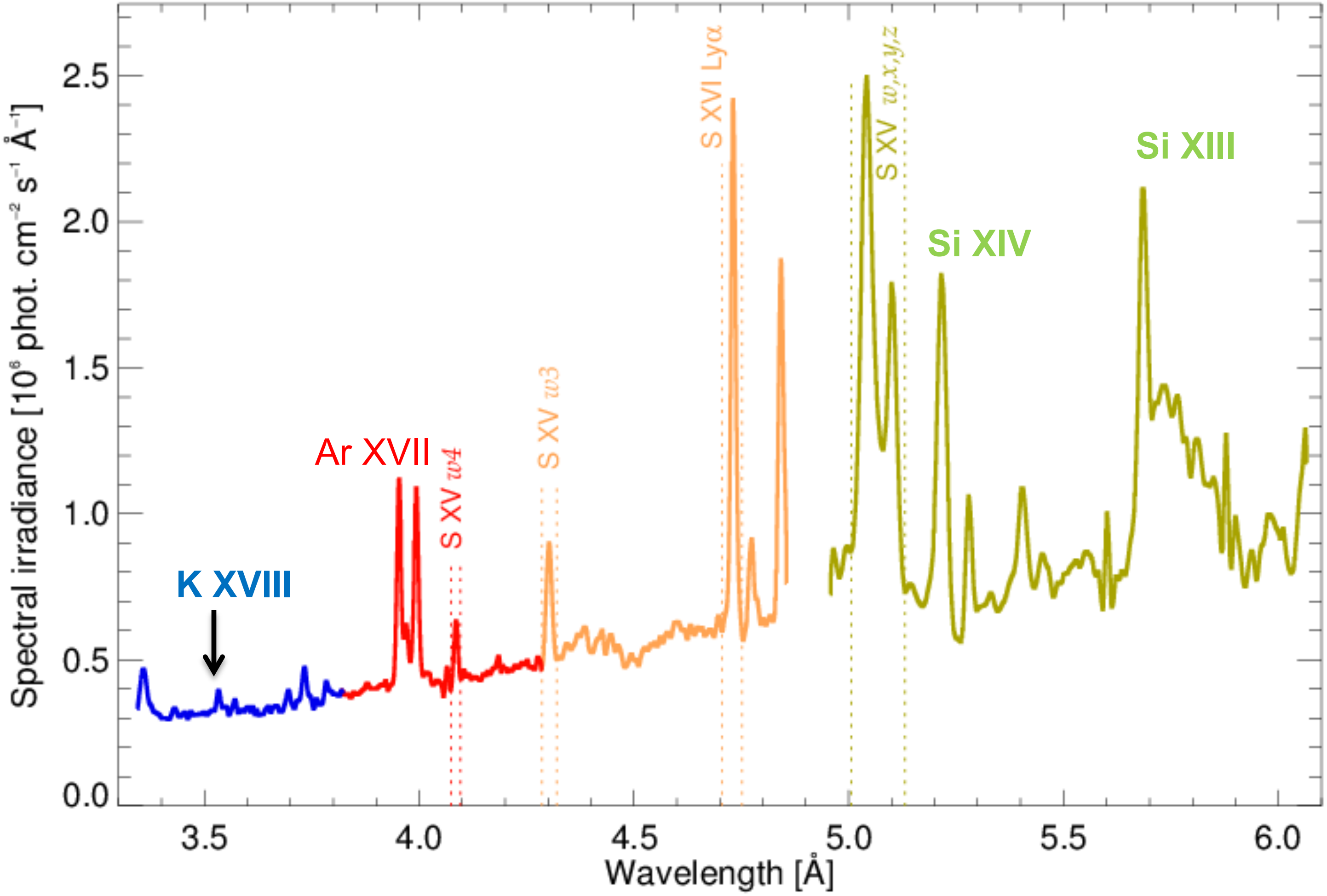
We have analyzed a total of 28 RESIK flares (Aug. 3, 2002 to March 17, 2003), with *GOES* X-ray classification B7 to X1.5 - a huge (x200) range.

In Dec. 2002, after some experimentation, the PHAs were adjusted to their optimum values.

This allowed the continuum to be eliminated entirely for channels 1 & 2 (3.40-4.27Å) and accurately estimated for channels 3 & 4 (4.35-6.05Å).

Absolute abundance estimates have now been made for K, Ar, Cl, S, and Si – this includes low-FIP and high-FIP elements.

Typical RESIK solar flare spectrum



Simple assumptions possible for flares

For high-temperature lines emitted by flare plasmas, it appears that an isothermal assumption is adequate.

This may be because (a) most of the high-T flare emission is from a single loop which is isothermal over much of its length; or (b) the temperature is a “characteristic” temperature of a system of several loops.

We are now re-visiting this assumption for lower-temperature (S and Si) lines in work over the past few weeks, using DEMs.

G(T) plots

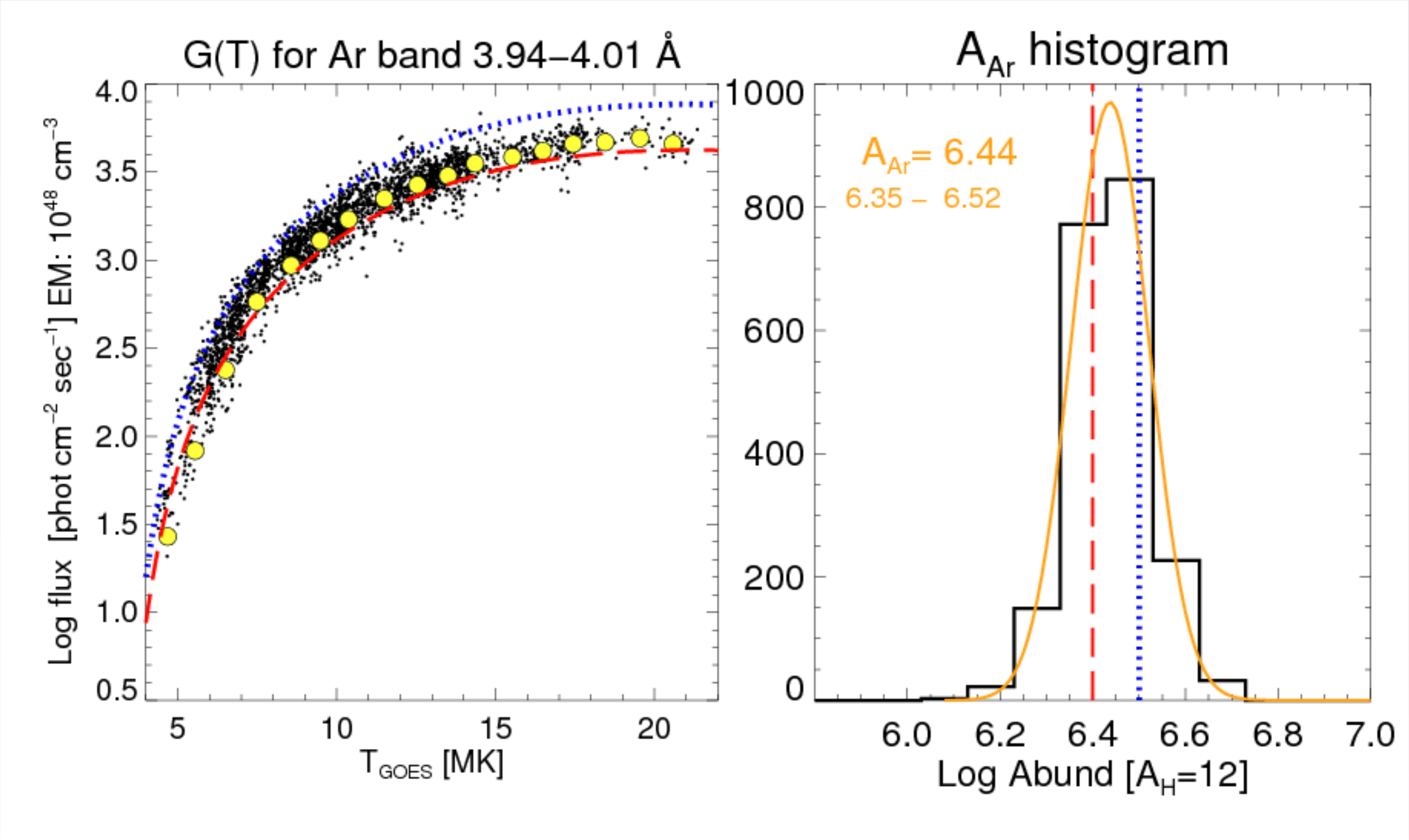
We can test accuracy of this isothermal assumption for various X-ray emission lines emitted by flare plasmas.

We plot RESIK line flux / emission measure from *GOES vs*. temperature from *GOES* for each spectrum, and compare with the theoretical G(T) (line contribution function) from CHIANTI.

We call these “G(T) plots”.

From them we estimate the element abundance.

Results from RESIK: Ar XVII lines

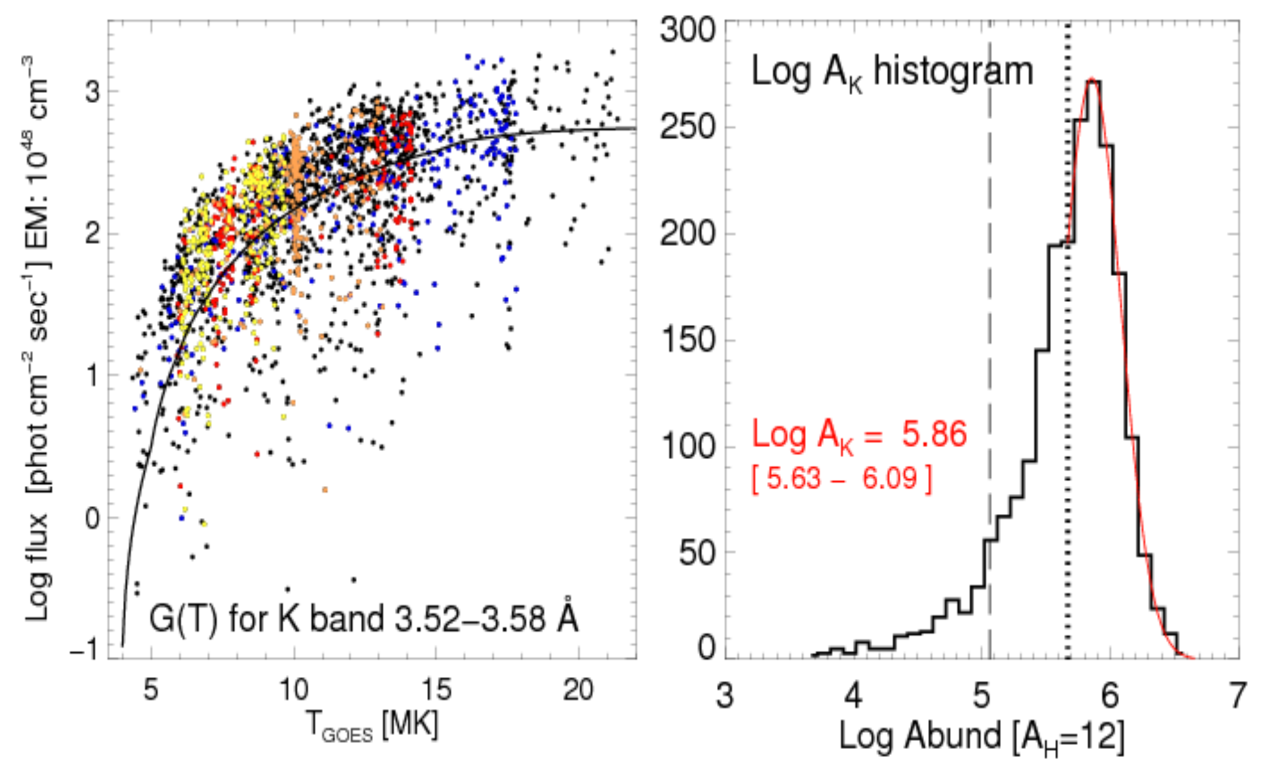


Red dashed line = solar proxies; blue dotted line = from meteorites

Ar XVII lines are strong, so the A(Ar) determination should be very reliable. A(Ar) = 6.45 ± 0.07

Sylwester et al. (2010) *ApJ*, 720, 1721

Results from RESIK: K XVIII lines

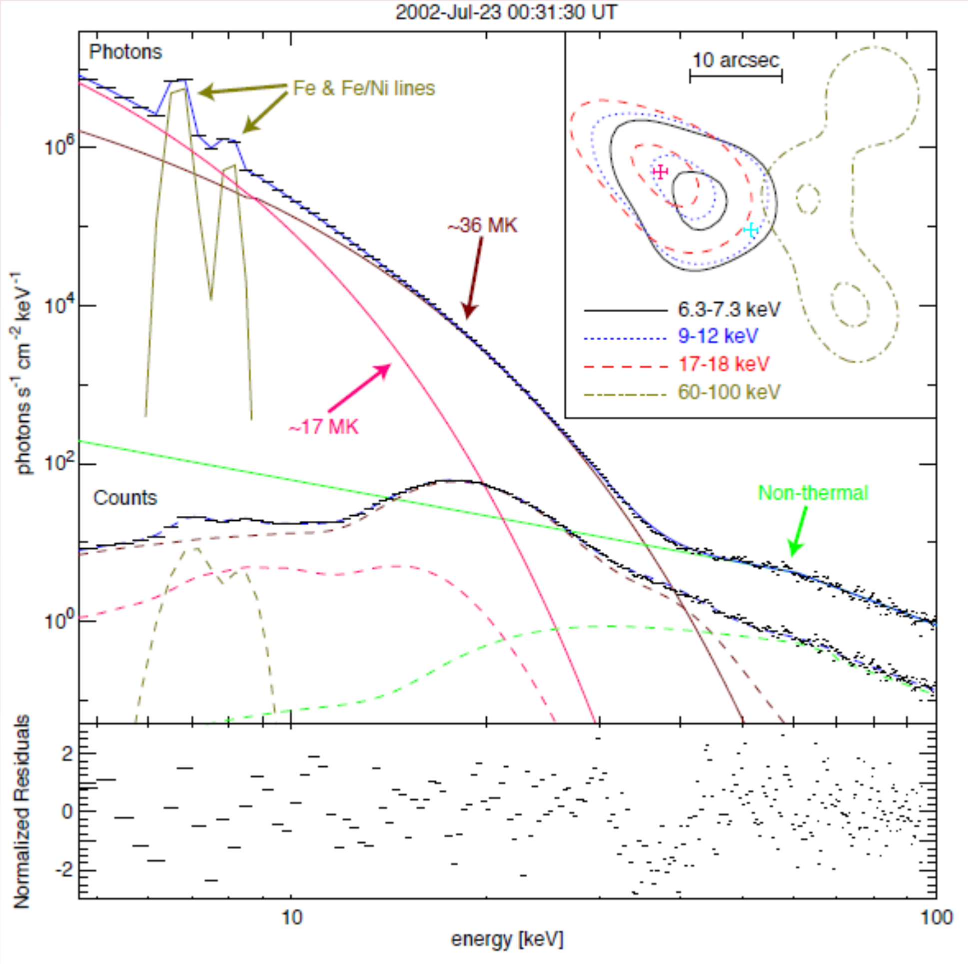


Dashed line = photospheric; dotted line = Doschek et al. (1985)

Note: K XVIII lines are very weak (never clearly seen before). A(K) = 5.86 ± 0.20

Sylwester et al. (2010) *ApJ* 710, 804

Fe lines in a RHESSI flare spectrum



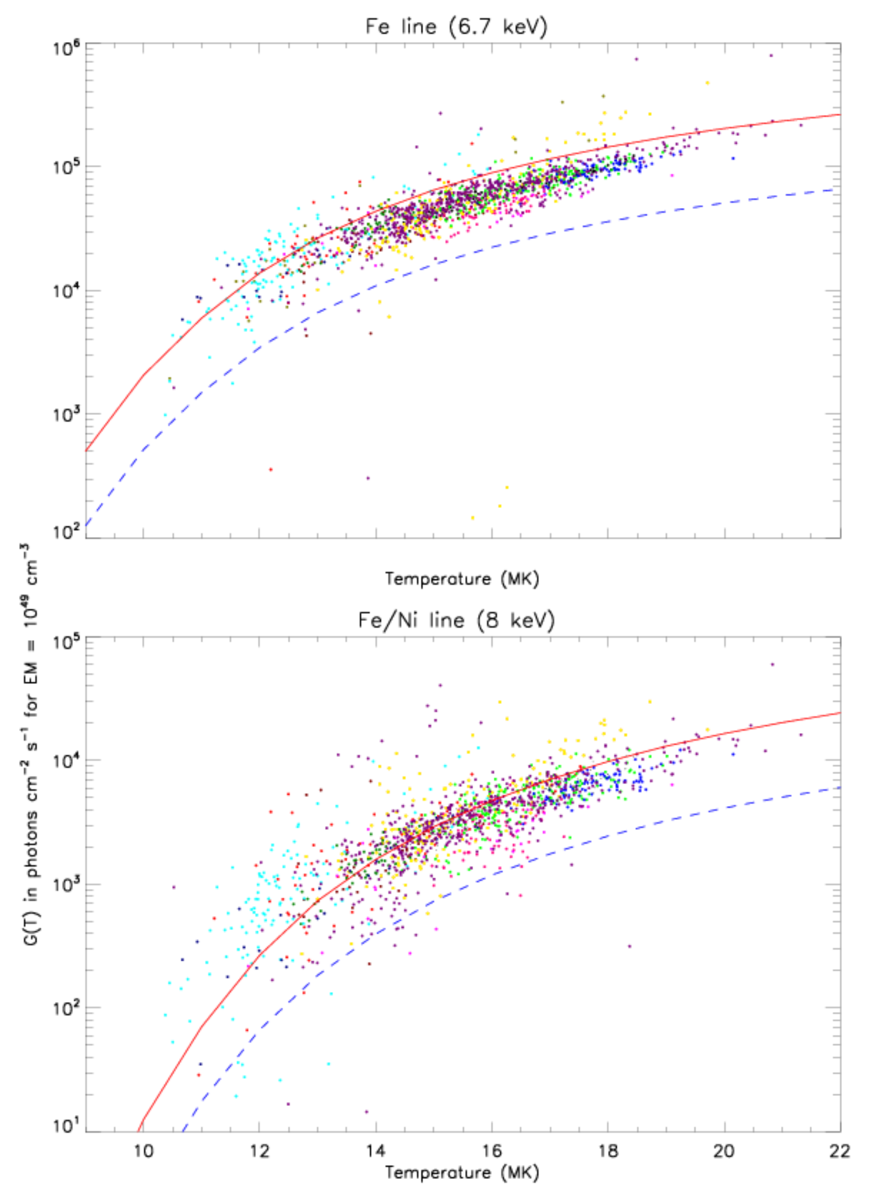
Caspi & Lin (2011 ApJ)

Note: flux and energy scales are both logarithmic.

G(T) plots for RHESSI Fe (6.7 keV) and Fe/Ni (8 keV) line features

From 2213 spectra, 24 flares:

A(Fe) = 7.91 ± 0.10



RESIK: solar flare element abundances

Element abundances (H=12)

Element (FIP in eV)	*Flare coronal (log scale) (H = 12)*	*Photospheric (log scale)*	*Enhancement factor (coronal/photosph.)*
Si (8.2)	7.91 ± 0.15	7.51 ± 0.03	2.5 ± 1.0
S (10.6)	7.16 ± 0.17	7.12 ± 0.03	1.1 ± 0.5
Cl (13.0)	5.75 ± 0.26	5.5 ± 0.3**	1.8 ± ??
Ar (15.8)	6.45 ± 0.07	6.40 ± 0.13	1.1 ± 0.25
K (4.3)	5.86 ± 0.20	5.03 ± 0.09	6.8 ± 4
Fe* (7.9)	7.91 ± 0.10	7.50 ± 0.04	2.6 ± 0.6

* *From RHESSI spectra*.

** *Photospheric based on single measurement from HCl in sunspot.*

Laming's ponderomotive force theory

Alfvén waves are like electromagnetic waves, with wave equation:

$$\frac{\partial^2 E_x}{\partial x^2} = \left(1 + \frac{c^2}{V_A^2}\right)\frac{1}{c^2}\frac{\partial^2 E_x}{\partial t^2}$$

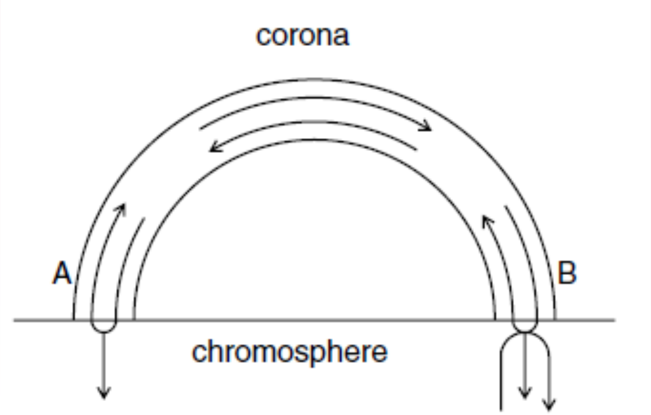
(V_A = Alfvén speed).

An ion with mass m and charge q is subject to a ponderomotive force

$$F_p = \frac{q^2}{4m\Omega^2}\frac{\partial^2 E_x}{\partial x^2} = \frac{mc^2}{4B^2}\frac{\partial^2 E_x}{\partial x^2}$$

which pulls ions upwards (or downwards). E.g. a resonant Alfvén wave going between 2 footpoints of a loop, A & B.

(Ω = ion gyrofrequency.)

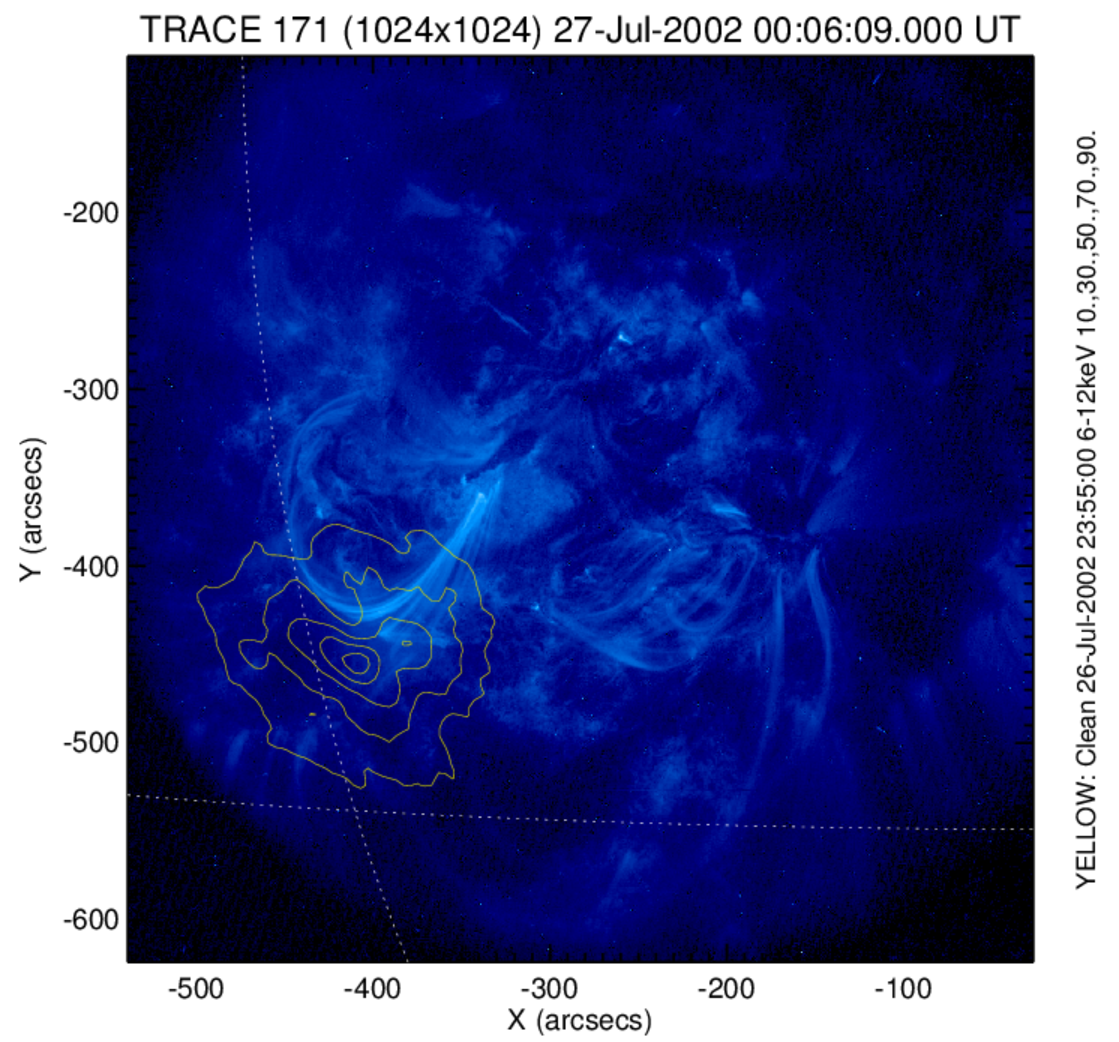


Abundances in flare with imaging data

TRACE and RHESSI both viewed this long-duration flare in July 2002.

Although not an ideal flare for RESIK (instrument parameters not yet optimized), we use it as typical example.

Main TRACE loop has 100,000 km length. Assume B=20G at loop top. Alfven speed ~ 2000 km/s, ω_A ~ 0.06 rad/s. This is roughly what Laming (2012) considers.



Laming calculations for flare loop

Fractionations (coronal element abundance / photospheric abundance) are given for a similar loop to the one observed: L = 100,000 km, B = 20 G, resonant Alfven frequency 0.07 rad/s.

Initially waves with an amplitude of 0.4 km/s are excited, travel along the loop, ending up with a peak amplitude of 55 km/s.

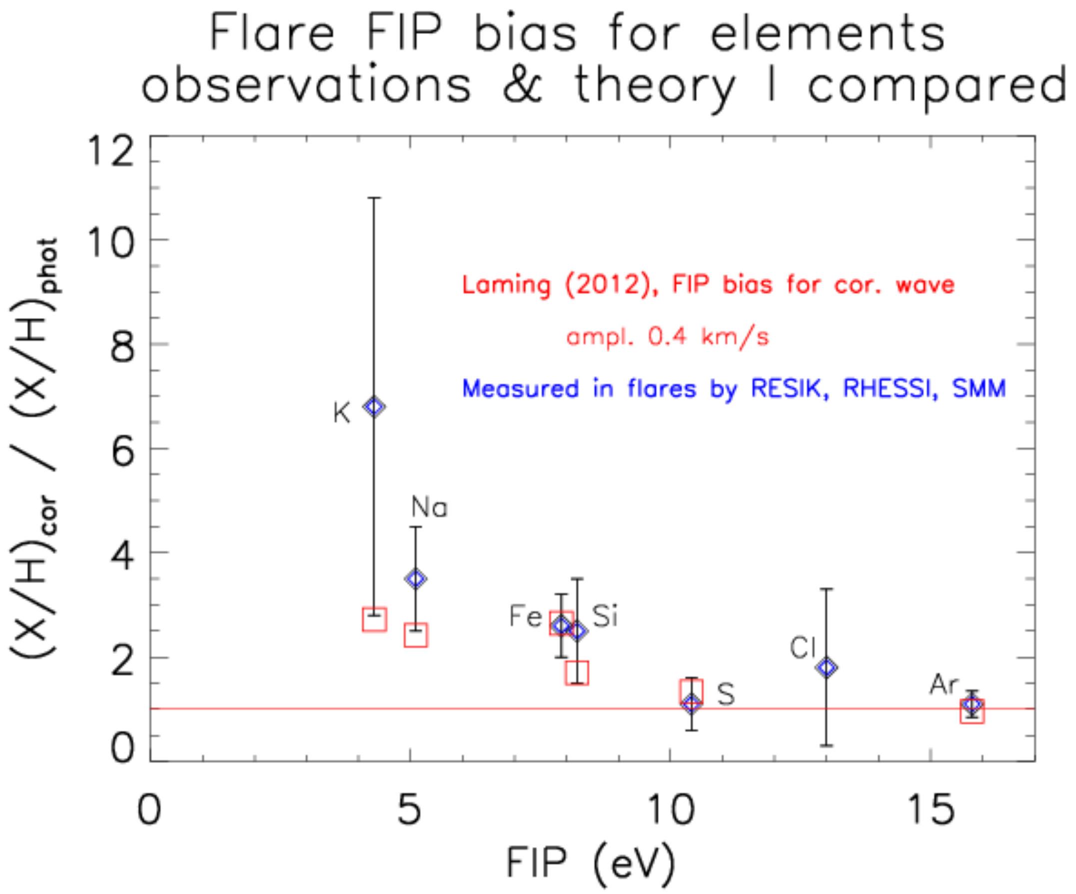
These are calculated and observed fractionations:

	Na*	Si	S	Cl	Ar	K	Fe**
Laming	3.5	1.7	1.3	?	1.1	2.7	2.6
RESIK	3.5	2.5	1.1	1.8	1.1	6.8	2.6
etc.	±1.0	±1.0	± .5	± ?	±.25	±4.0	±.6

* *From SMM measurement of a single spectrum.*

** *From RHESSI flares.*

Observed FIP bias vs. Laming (2012) theory:



Summary and conclusions

RESIK spectra have enabled the flare abundances of Si, S, Cl, Ar, K to be determined on the assumption of an isothermal plasma (*T* = GOES temperature).

Si, K (and Na, Fe) are enhanced in flare plasmas over photospheric. S, Cl, Ar are probably close to photospheric abundances.

Trying to relate this to Laming's ponderomotive theory is not easy – the uncertainties are large. But the theory is promising.

We are now working on a multi-temperature analysis (this may affect Si, S results).

New X-ray observations with a well-calibrated instrument like RESIK are needed: SolPEX on the ISS Russian module is eagerly anticipated.