The Importance of Iron in Solar Physics

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Helen Mason's Birthday Fest, September 2010

Importance of Iron

Fe has a solar photospheric abundance of only **Fe/H = 3.2 x 10^{-5}** (Asplund et al. 2009) but its importance far outweighs its abundance.

Its complex atomic structure gives rise to numerous spectral lines in the visible, due both to neutral and first-ionized stages (Fe I and Fe II).

At higher temperatures, when Fe is ionized to much higher stages, there are numerous emission lines in the ultraviolet, extreme ultraviolet, and X-ray regions.

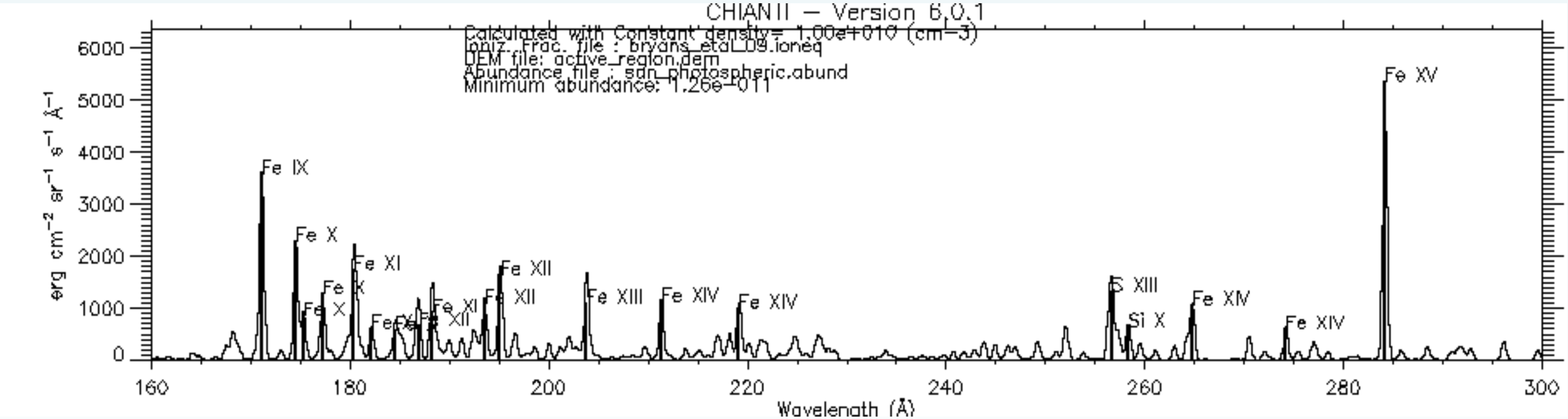
Fe as an important radiator

At coronal temperatures (1-2 MK), there are several very intense lines:

Fe IX $3p^6 – 3p^5\ 3d$	171 Å
Fe X $3p^5 – 3p^4\ 3d$	174.8, 177.2 Å
Fe XI $3p^4 – 3p^3\ 3d$	180.4, 188.3 Å
Fe XII $3p^3 – 3p^2\ 3d$	192 Å
Fe XIII $3p^2 – 3p\ 3d$	202 Å
Fe XIV $3p – 3d$	211.3 Å
Fe XV $3s^2 – 3s3p$	284.1 Å

Importance of these EUV lines

Lines of Fe IX – Fe XV dominate the quiet Sun corona: the amount of energy in them far surpasses any other emission line in the entire solar X-ray and EUV spectrum.



Active region spectrum 160-180 Å: CHIANTI simulation

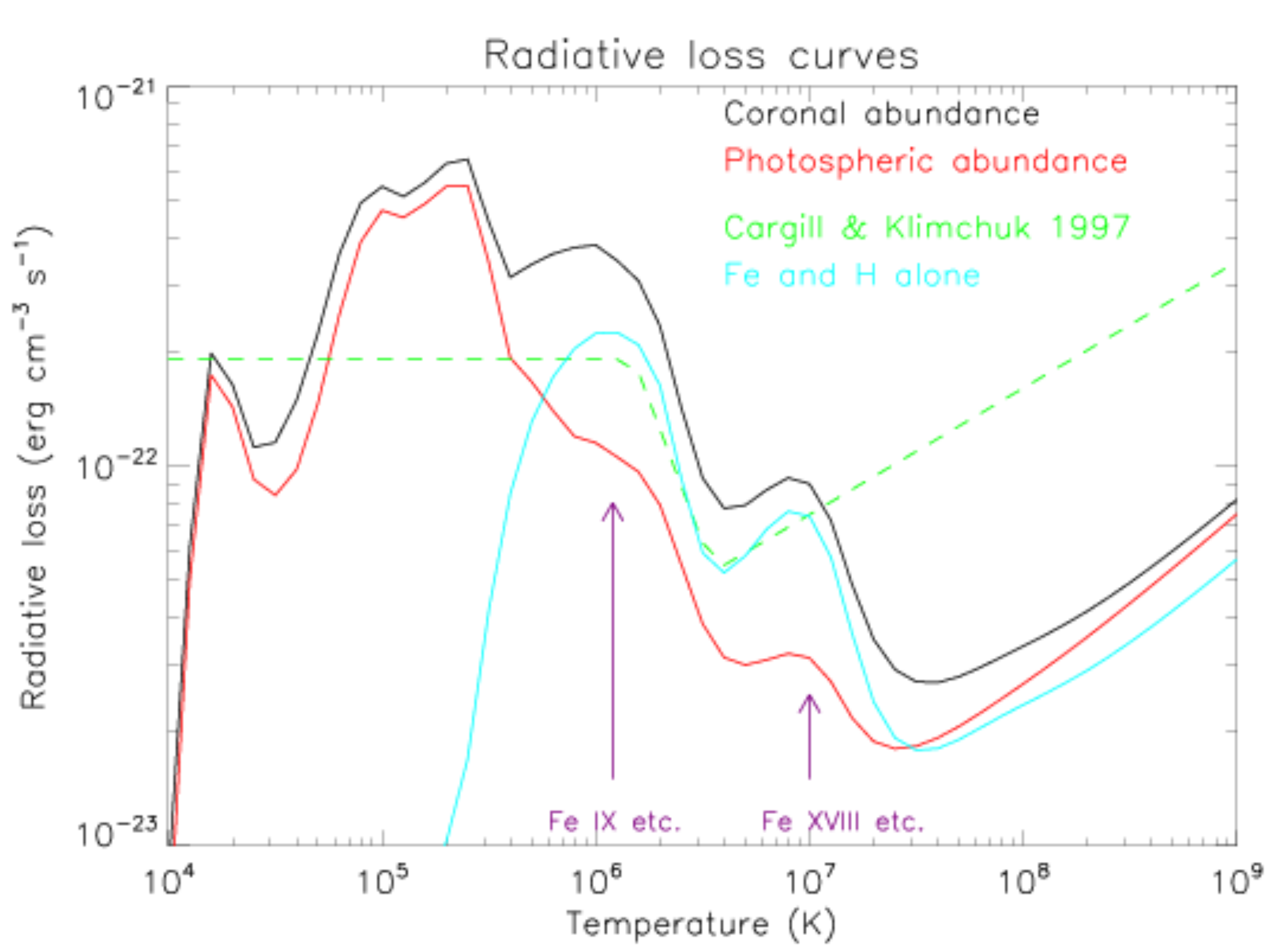
X-ray lines: higher ionization stages of Fe

For temperatures in the 5-20 MK range, Fe is ionized to much higher stages: Fe XVIII – Fe XXV.

Emission lines due to Fe XVIII to Fe XXIV are very important in active regions and flares.

The lines are mostly due to 2p – 3d or 2p – 3s transitions (e.g. 2p—3d line of Fe XXIV at 11.2 Å).

Radiative loss functions for solar compositions



Fe ion emission accounts for peaks at 10^6 and 10^7 K

Green line: Cargill & Klimchuk 1997 (ApJ, 478, 799)

Electron densities from Fe lines in flares

Take case of Fe XXI = C-like Fe. The ground configuration is $1s^2\ 2s^2\ 2p^2$.

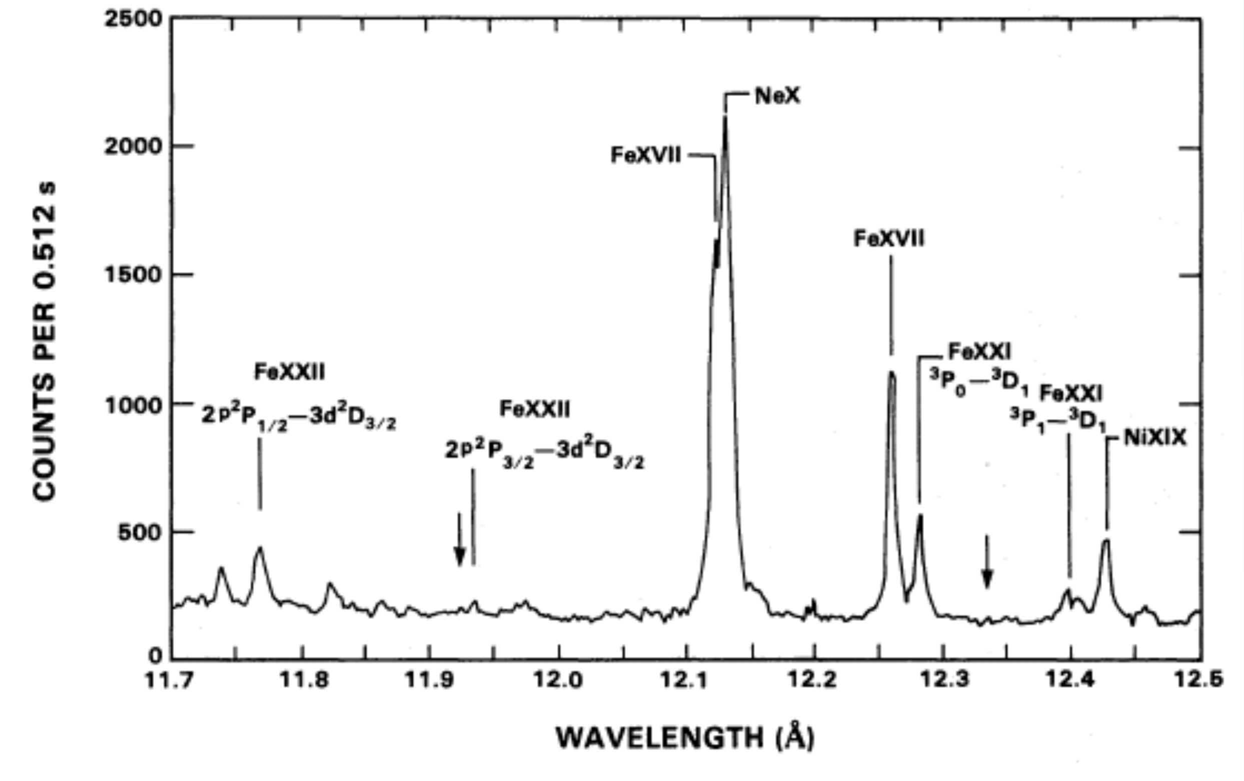
Combining all the orbital and spin angular momenta, it turns out that there are 5 possible atomic states.

At $N_e = 10^{12}$ cm^{-3} or less, only the ground level $^3P_0$ is populated.

But at higher densities, the other 4 levels are populated, and many more X-ray lines become excited.

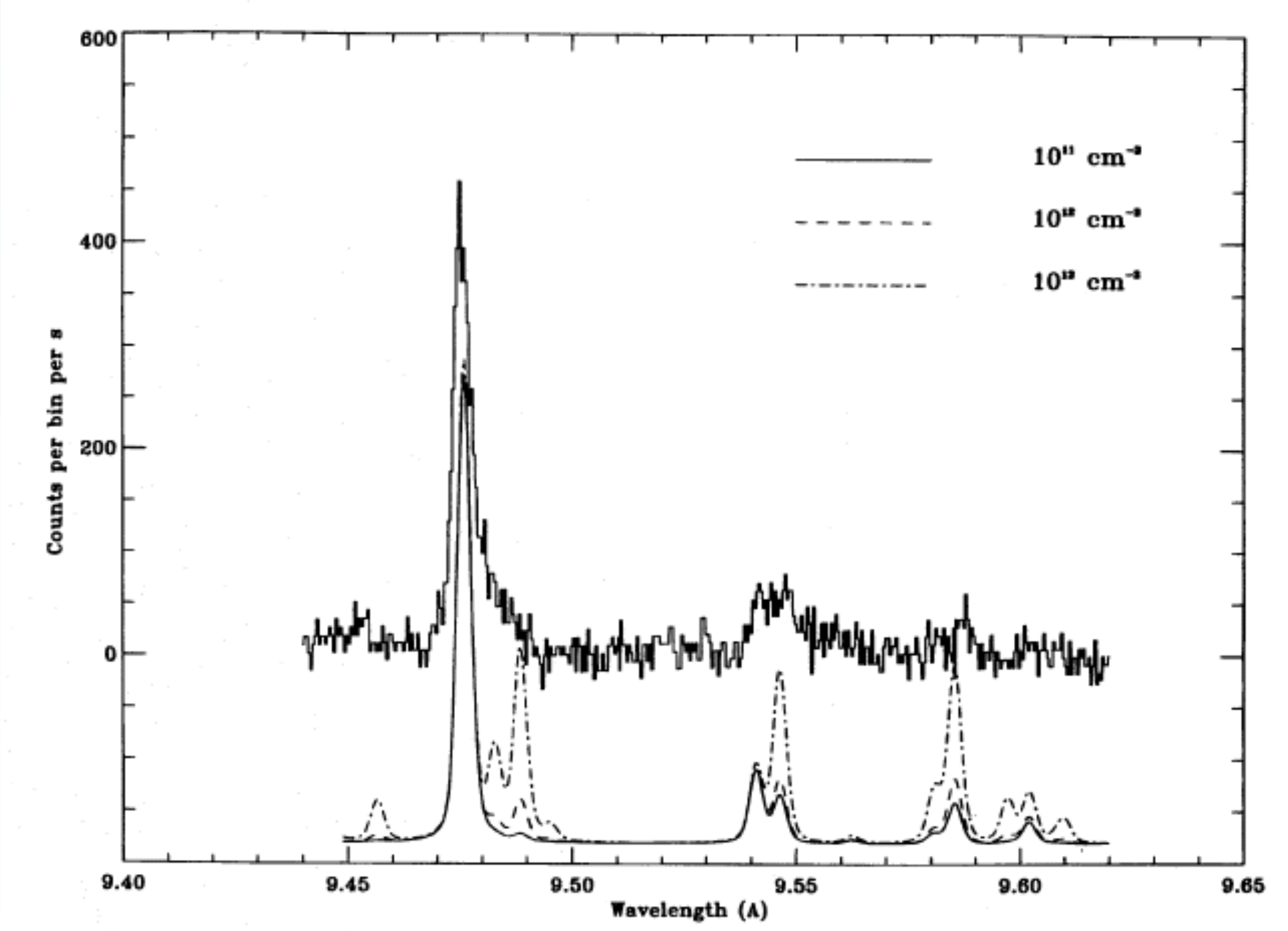
Helen's work in 1980s provided interesting diagnostic potential for X-ray lines emitted by flares.

Flare electron densities from Fe XXI X-ray lines



SMM FCS scan of the 11.7-12.6 Å during the decay of the 1980 August 25 flare. Absence of Fe XXI and Fe XXII lines (arrows) imply $N_e < 10^{12}$ cm^{-3}: Mason & Storey (1980) and Mason et al. (1979).

Fe XXI lines in a large flare: SMM



Fe XXI lines at 9.4 to 9.6 Å during the onset of an M4.5 flare, 1985 July 2 (Phillips, Bhatia, Mason, & Zarro 1996).

N_e ~ 2-3 x 10^{12} cm^{-3}!

High densities in flares: the implications

Are such high densities (> 10^{12} cm^{-3}) in flares plausible?

Only if this was a short-lived event: the radiative cooling time is

$$\tau_{rad} = \frac{3k\Delta T_e}{N_e R(T_e)}$$

and for N_e = 2-3 x10^{12} cm^{-3}, τ_{rad} is only ~1.5 s.

We speculated in our paper that, as the FCS just happened to scan through the region of the Fe XXI /Fe XXII lines at the flare onset stage, the high-density was only short-lived: the flare `kernel' probably expanded very shortly after and N_e was ~10^{11} cm^{-3}.

The abundance of Fe in coronal plasmas: FIP Effect

Meyer (1982) and Feldman (1992) found evidence that the coronal abundances of elements with small (<10 eV) values of first ionization potential (FIP) were enhanced over photospheric values.

This includes Fe (FIP = 7.9 eV).

Young & Mason (1997) found evidence for Mg/Ne ratios with both photospheric and coronal values in an AR.

White et al. (2000) used thermal bremsstrahlung radio emission and SOHO/CDS Fe lines in an active region to deduce Fe/H = 4 x photospheric abundance.

RHESSI broad-band spectrometer

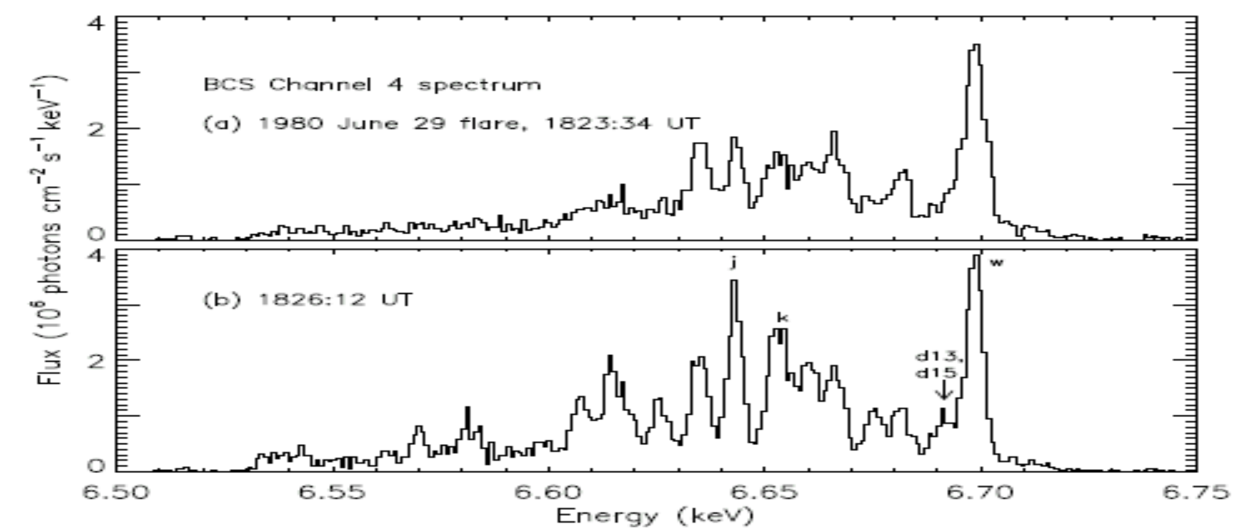
RHESSI is an X-ray and gamma-ray imager /spectrometer operating in the 3 keV to 7 MeV range.

However, it does see down to energies < 10 keV which therefore includes the group of highly ionized Fe lines at 6.7 keV (1.85 Å).

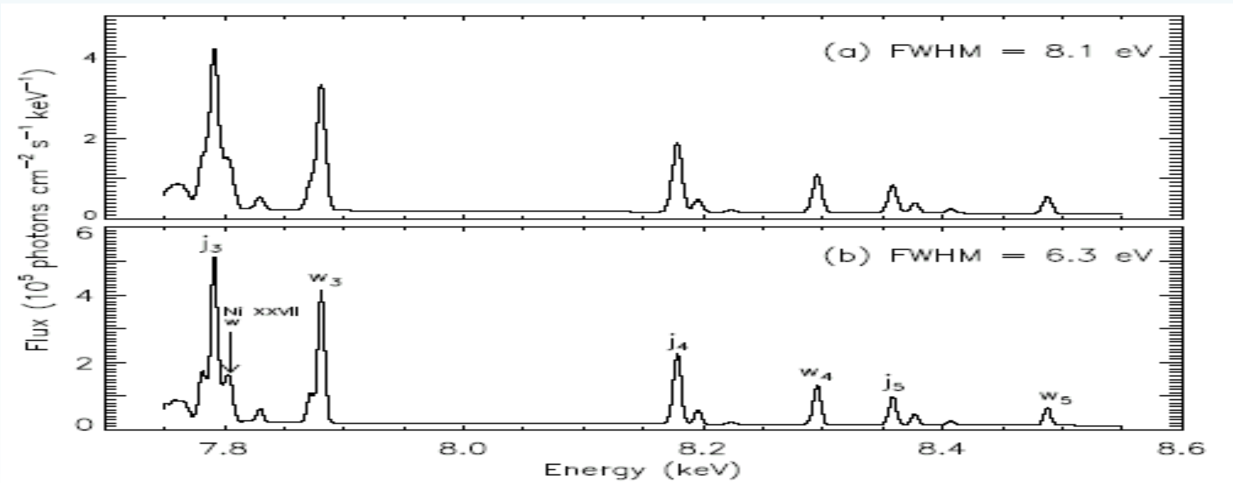
It also includes another group of Fe lines at 8 keV (1.55 Å).

These lines include Fe XXV (He-like Fe) lines and numerous dielectronic satellites of Fe XXIV and lower stages.

The 6.7 keV and 8 keV spectra of Fe lines

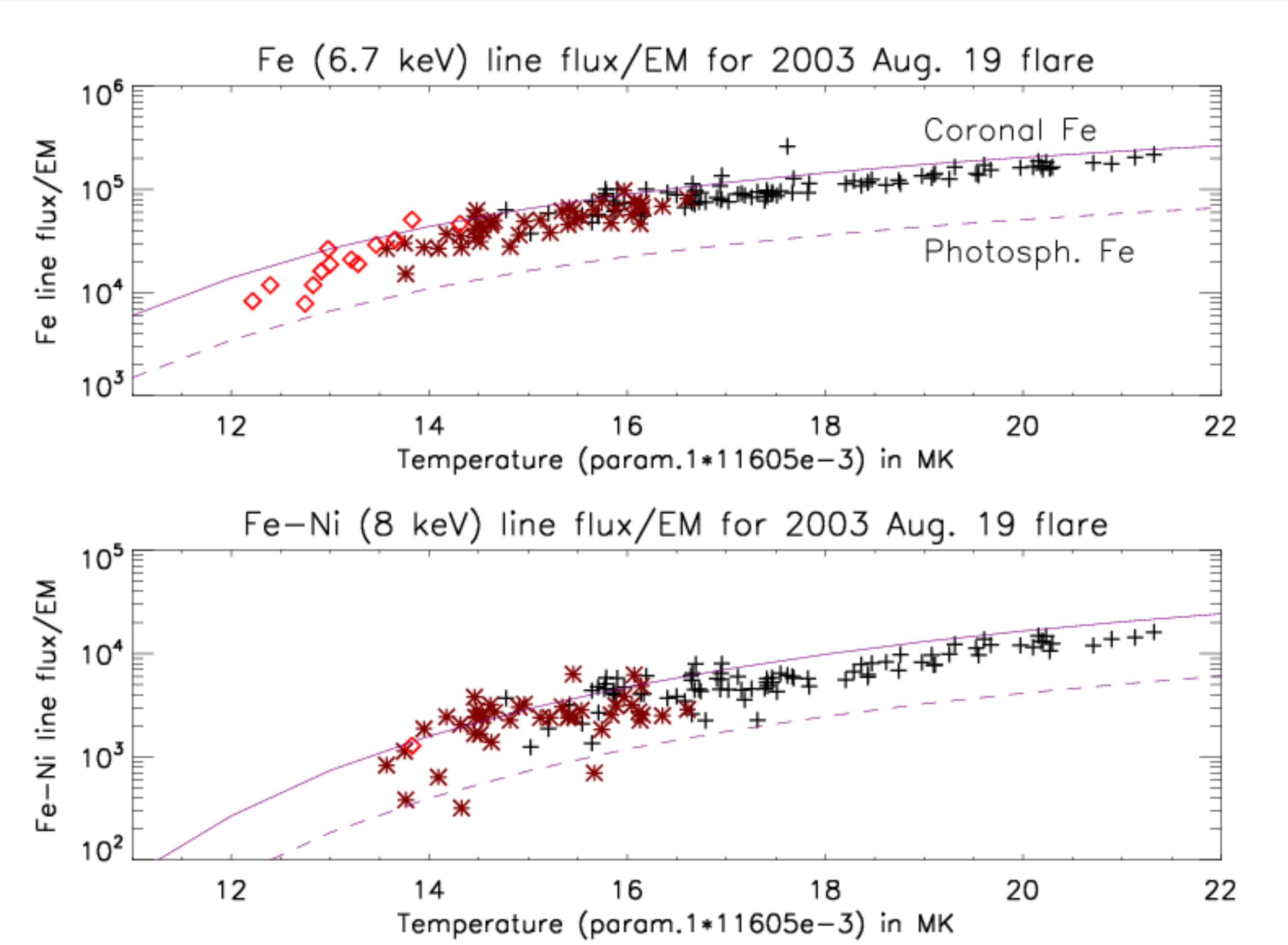


Lines in the 6.7 keV complex (SMM BCS)



Lines in the 8 keV complex (theoretical)

RHESSI observations of the 6.7 keV and 8 keV Fe line features



Example of obs. line flux/EM and theor. curves: Fe/H ~ 3 x photospheric

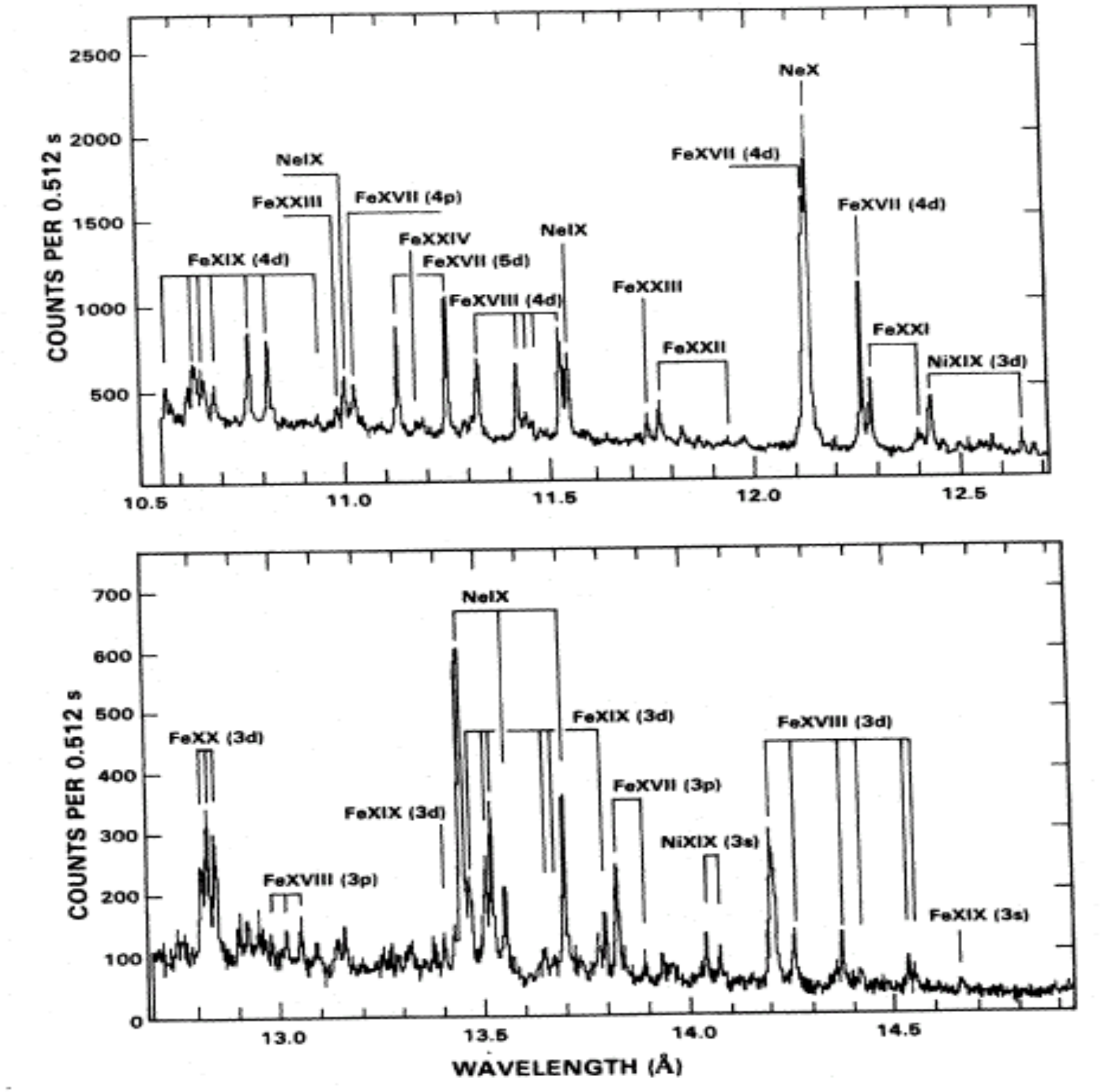
Concluding Remarks

Although Fe has an abundance of 32 ppm in the solar photosphere, its importance as a radiator and absorber is enormous.

In the EUV and X-ray regions, the many lines of Fe ions enable temperature and density to be evaluated for active regions and flares, often with surprising results. Helen's work has been central to this.

Its abundance in the corona appears to be 3 or 4 times its photospheric value, based on EUV and X-ray line emission, a confirmation of the FIP effect.

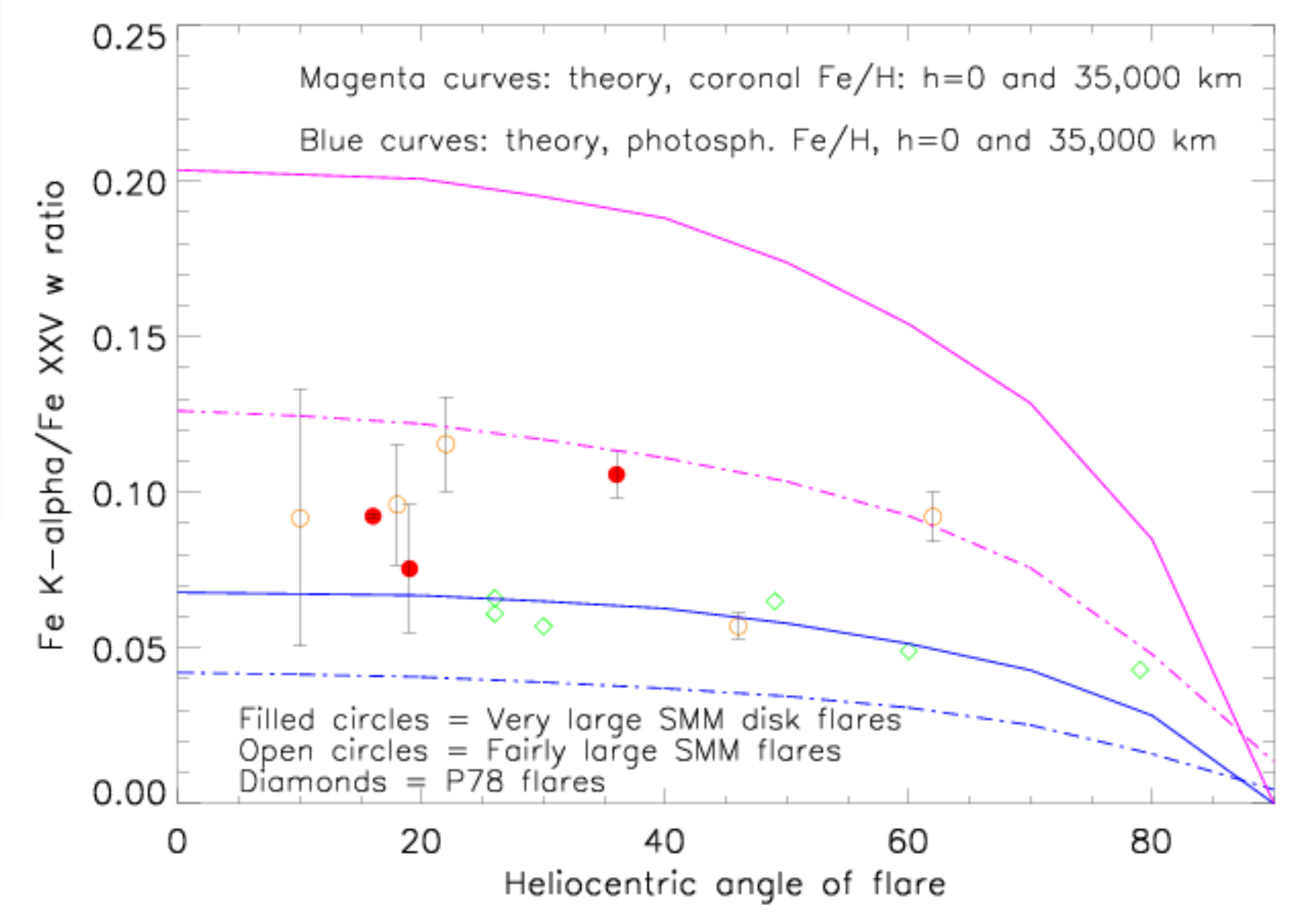
Solar flare X-ray spectra: importance of Fe lines



Scan through the 10-15 Å region during the decay of anM3 flare on 1980 August 25 with crystal spectrometer on SMM.

Fe ion stages from Fe XVII to Fe XXIV represented: T=5MK to 13MK (Landi & Phillips 2005)

Fe K-alpha / Fe XXV w line ratio



Fe K-alpha is formed by fluorescence, and is formed in the photosphere. Fe XXV is formed in hot flare plasmas in the corona

Radiative and convection zones in solar interior

In the solar interior, proceeding outward from the core, the temperature steadily drops from 15 MK to ~1 MK -- Fe ions start to recombine to stages like Fe IX-Fe XV and absorb at these wavelengths, giving rise to a sudden increase of opacity.

Hence radiation ceases to be the main energy transport: beyond this level (approx. 0.7 R_O), convection is the chief transport mechanism.