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Solar Flare Particle Acceleration - a spectroscopic viewpoint

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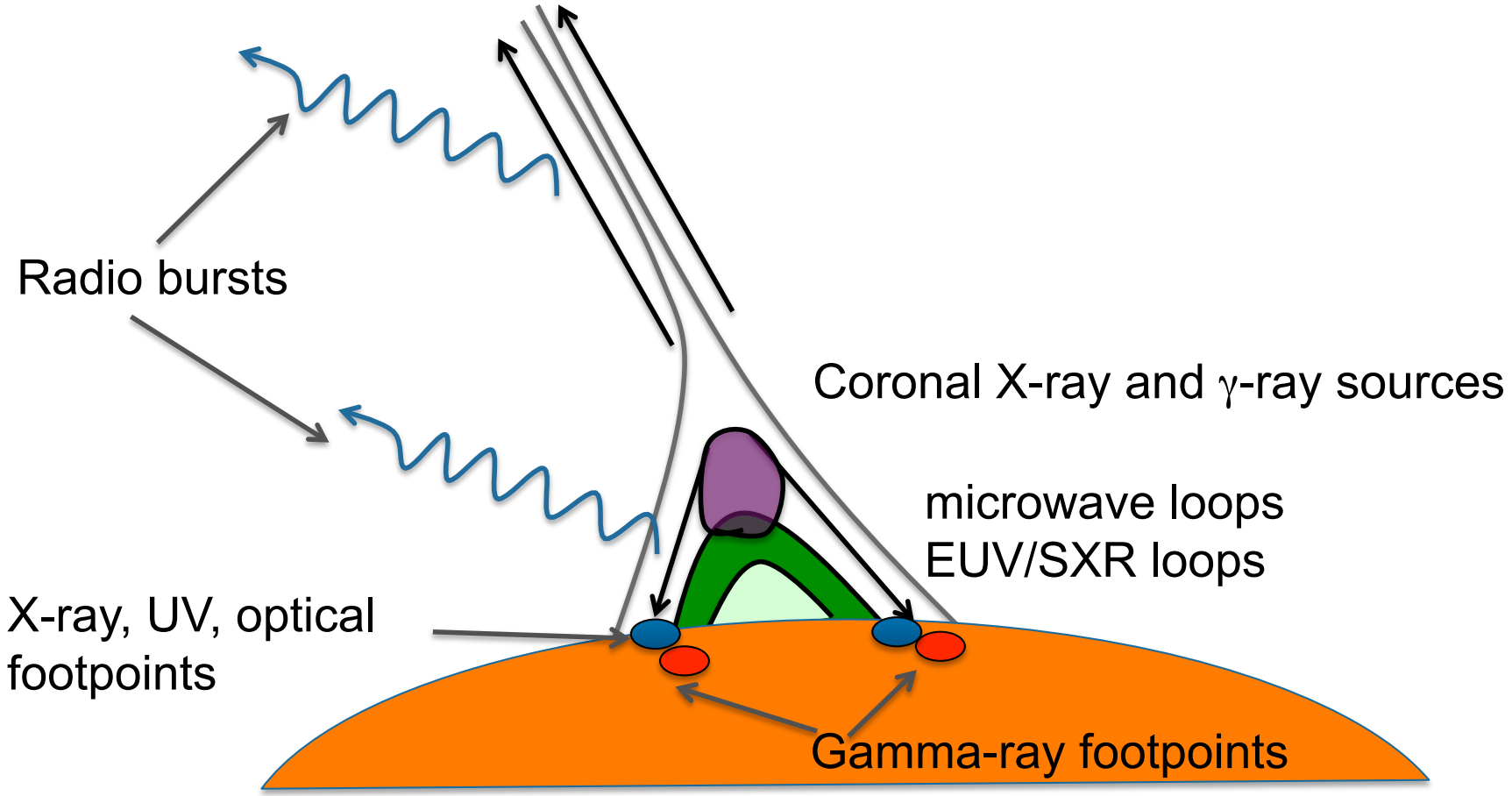
A broad view of flare spectroscopy

Flare spectroscopy includes atomic, nuclear and plasma wave spectroscopy

Only the HXR continuum, and a few lines like Hα, have been <u>significantly</u> exploited for flare impulsive phase electron diagnostics



Electrons in corona and chromosphere

During a flare, accelerated particles are present in both corona and chromosphere

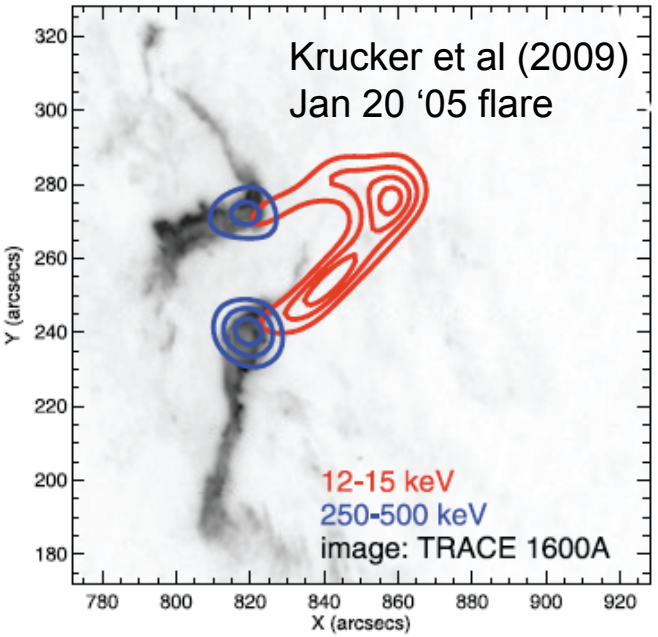
Populations usually assumed to be one and the same (though not necessarily the case)

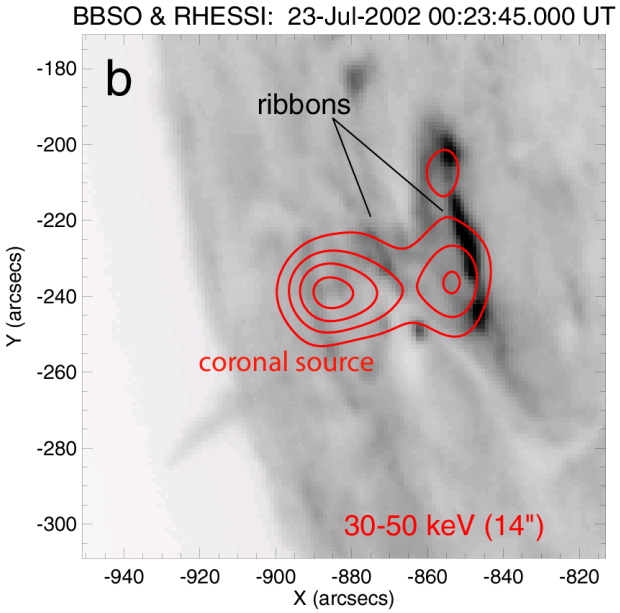
The term ‘flare lines’ usually refers to the highly-ionised states present at 10-20 MK (corona)

BUT

During a flare the chromosphere provides the bulk of the radiation from EUV to IR

- relatively untapped as a source of diagnostic information (see Hudson talk)





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SXR flare spectroscopy

Main recent instruments for SXR spectroscopy: FCS on SMM and BCS on *Yohkoh.* Famously used to establish flare momentum balance (e.g. Antonucci et al. 1984, Zarro et al 1988, Canfield et al. 1990)

Some particularly noteworthy results for near impulsive phase

- Very high plasma densities ($n_e > 10^{12}$/cc), with small volumes (10^{23} cm^3) at high temperatures (~10MK) with SMM (Phillips et al '96)

- Increase in non-thermal velocities before flare impulsive phase (with BCS e.g. Alexander et al '98, Harra et al '01) – ***preflare heating/ turbulence? Link to accelerator?***

- Location of non-thermal velocities with BCS – ***footpoints*** (Mariska et al. 1993, 1996, Harra-Murnion et al 1997) ***or looptops?*** (Khan et al 1995, Ranns et al 2000, 2001)

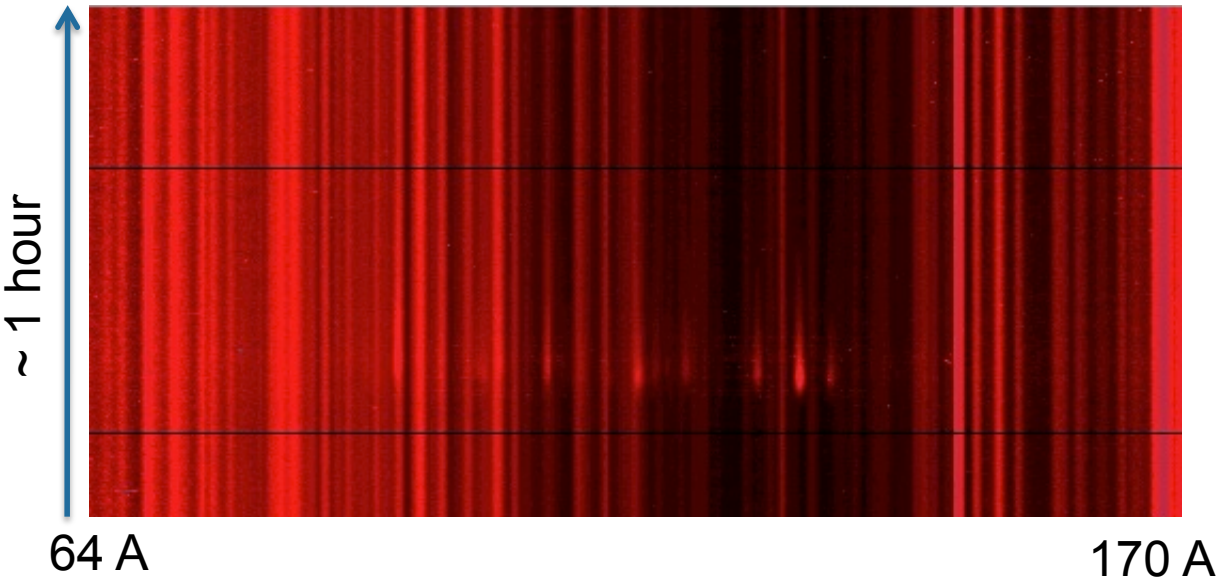
Several open questions about pre-flare energisation from these observations – need to return to SXR (imaging?) spectroscopy.

Broad-band UV/EUV

Broad-coverage EUV observations relatively few & far between

- OSO satellites (e.g. Hall 1971, Neupert 1973, etc.)
- NRL slitless spectrograph on Skylab (e.g. Doschek et al 77, Cook & Brueckne 79)
- SERTS rockets through the 90s (e.g Thomas & Neupert 1994)

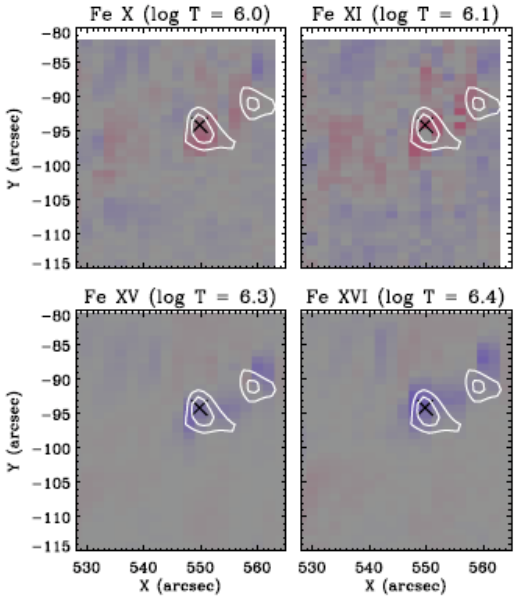
SDO/EVE (50A - 1000 A,+ Lyα) with 10s time resolution – good enough for impulsive phase – may open up this field again.

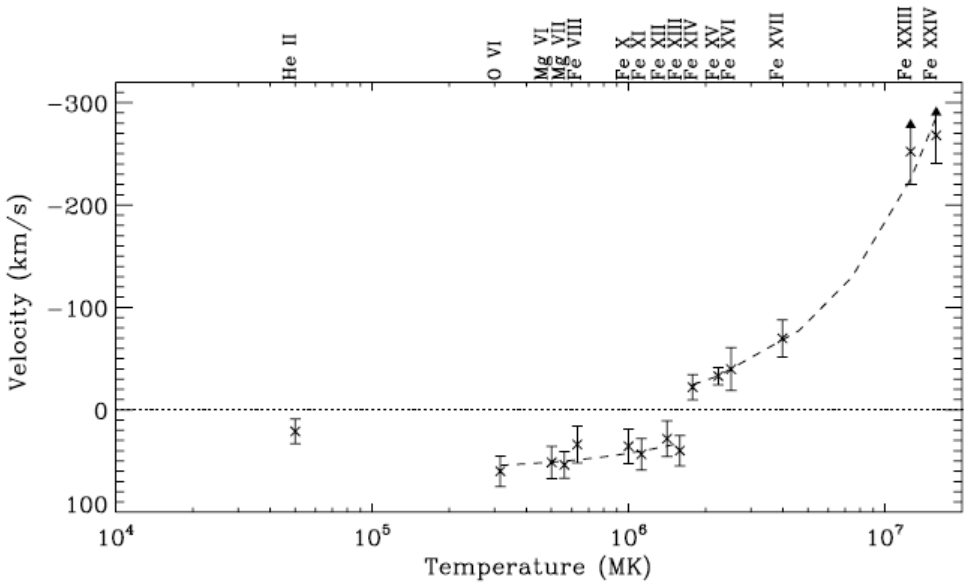


M2.0 flare, May 5 2010, image courtesy H. Hudson

EUV diagnostics: chromospheric footpoints

Chances of getting spectrometer slit on the same location as the HXR footpoints rather low – but it has been done (e.g. Brosius, Milligan).





Milligan et al. 2010 EIS/RHESSI study

Studies have mostly concentrated on upflow speed as a function of T, establishing chromospheric evaporation.

Velocities are undiscriminating in terms of understanding where & how energy deposited – need to use full range of EIS diagnostics (e.g. Watanabe et al 2010, Graham et al 2010)

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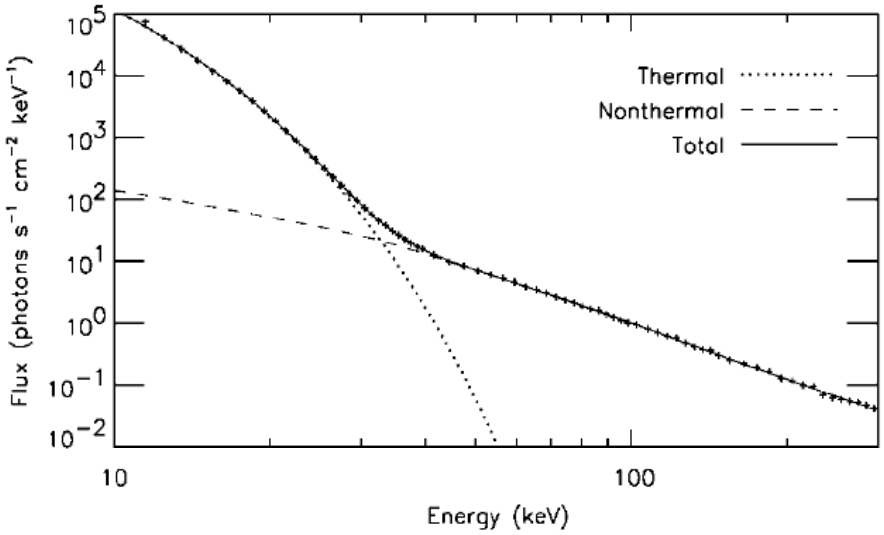
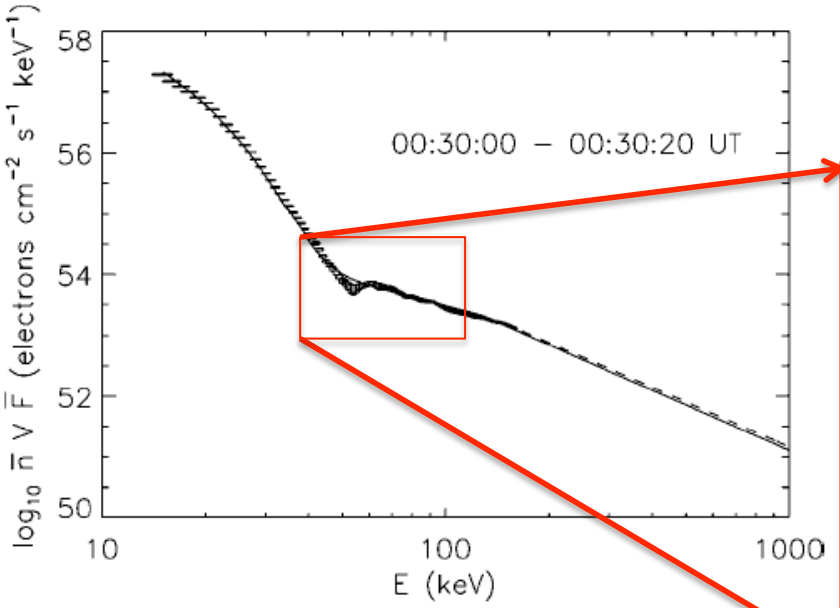
RHESSI spectroscopy



Usual approach for RHESSI spectroscopy is the non-thermal + power-law fit.

(Holman et al. 2003)



Piana et al. 2003

Regularised inverse methods show a richer picture.

$E)dE$

own

Non-thermal distributions

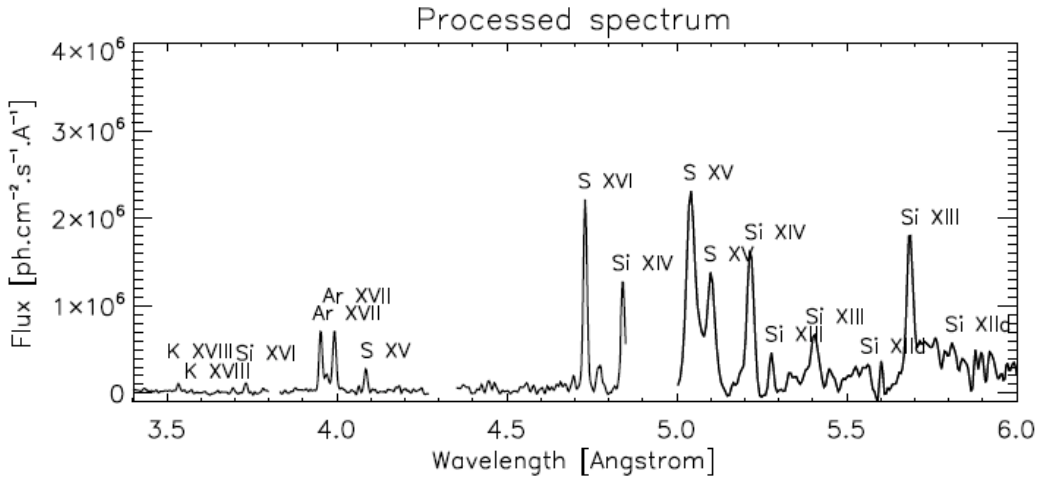
EUV line diagnostics for non-thermal electrons being investigated (e.g. Smith & Jordan 03; Feldman et al 07,08; Dzifčáková 92, 00 etc; Dzifčáková & Mason 2005)

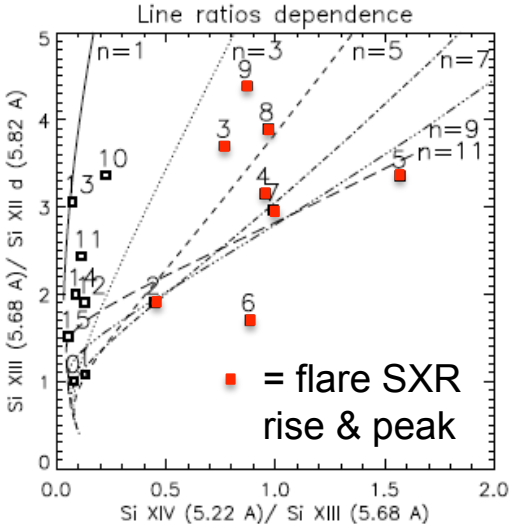
NB - 'Maxwellian + power-law' model is convenient, but has no particular theoretical justification in a flare.

Need to consider carefully more exotic distributions (κ, n distributions, return currents)

$$f_n(\mathcal{E})\mathrm{d}\mathcal{E} = \mathcal{B}^n \frac{2}{\sqrt{\pi}} \mathcal{E}^{\frac{n}{2}} (kT)^{-(\frac{n}{2}+1)} \exp(-\mathcal{E}/kT)\mathrm{d}\mathcal{E}$$

n = 1 is Maxwellian





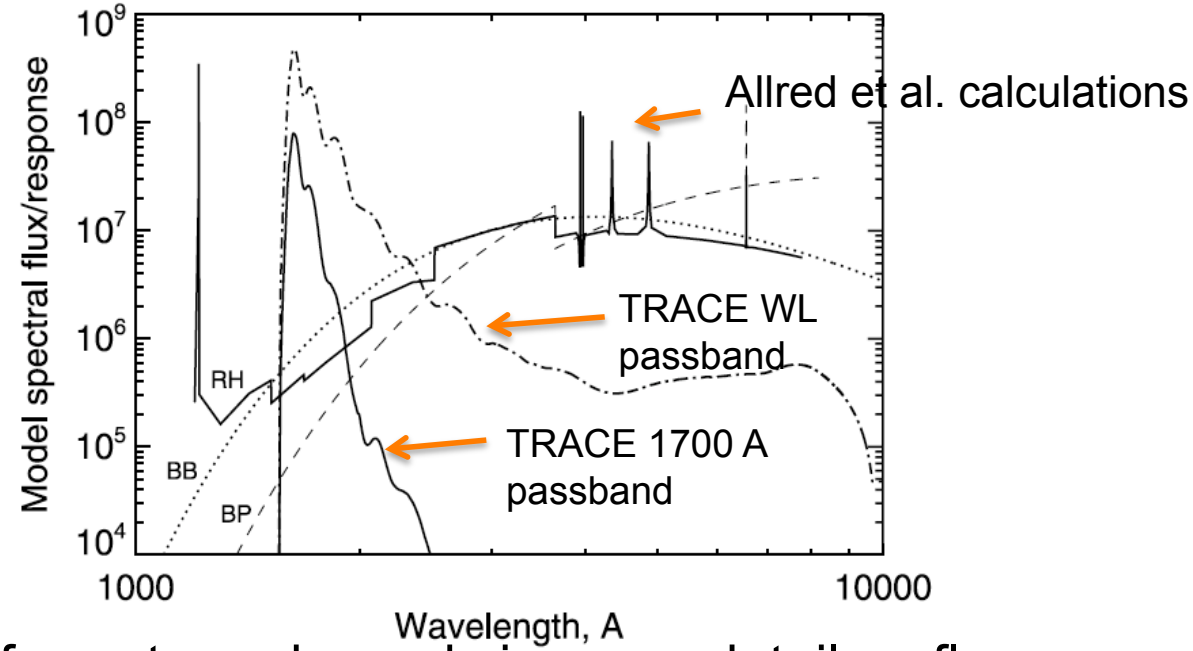
Dzifčáková et al. 2008

Broad-band UV/Optical spectra

Most of the electron energy is reprocessed in the chromosphere and emitted as UV-IR radiation – but observations limited

On the other hand, modeling is relatively advanced (e.g. Heinzel, Zharkova, Allred, Hawley)

e.g. Allred et al (2005) uses radiative hydrodynamics to calculate flare spectrum throughout July 23 2002 flare



Time evolution of spectrum depends in some detail on flare energy deposition model - clear need for broad spectral coverage of this region

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Closing thoughts

- Flare HXR imaging/spectroscopy has been our prime diagnostic for accelerated particles. But it is only ~ 10^{-4} of total flare radiative output

- SXR emission is about 10% in most flares (Dennis et al). – time to look here again.

- SDO/EVE should stimulate renewed interest in EUV diagnostics for flare plasmas (notwithstanding lack of imaging)

- The bulk of the flare radiative output is in the UV-optical range, pretty much untouched spectroscopically!

- Real need for UV & optical spectroscopic flare observations – looking forward to IRIS, Solar-C Plan B (?)

- Real need for more detailed modeling and atomic physics of non-thermal, non-equilibrium plasmas.