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Atomic Data Needs for Astrophysics

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Queen’s University Belfast

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Overview

- Status of CHIANTI & data needs
- Upcoming solar missions & data needs
  - Solar-B
  - SDO
- CHIANTI projects for assessing and calculating atomic data
  - n=3 transitions at UV wavelengths
  - FAC calculations for X-ray wavelengths
  - benchmarking of iron data
- Specific data problems
  - neutrals
  - Fe XVII
- Recombination & ionization

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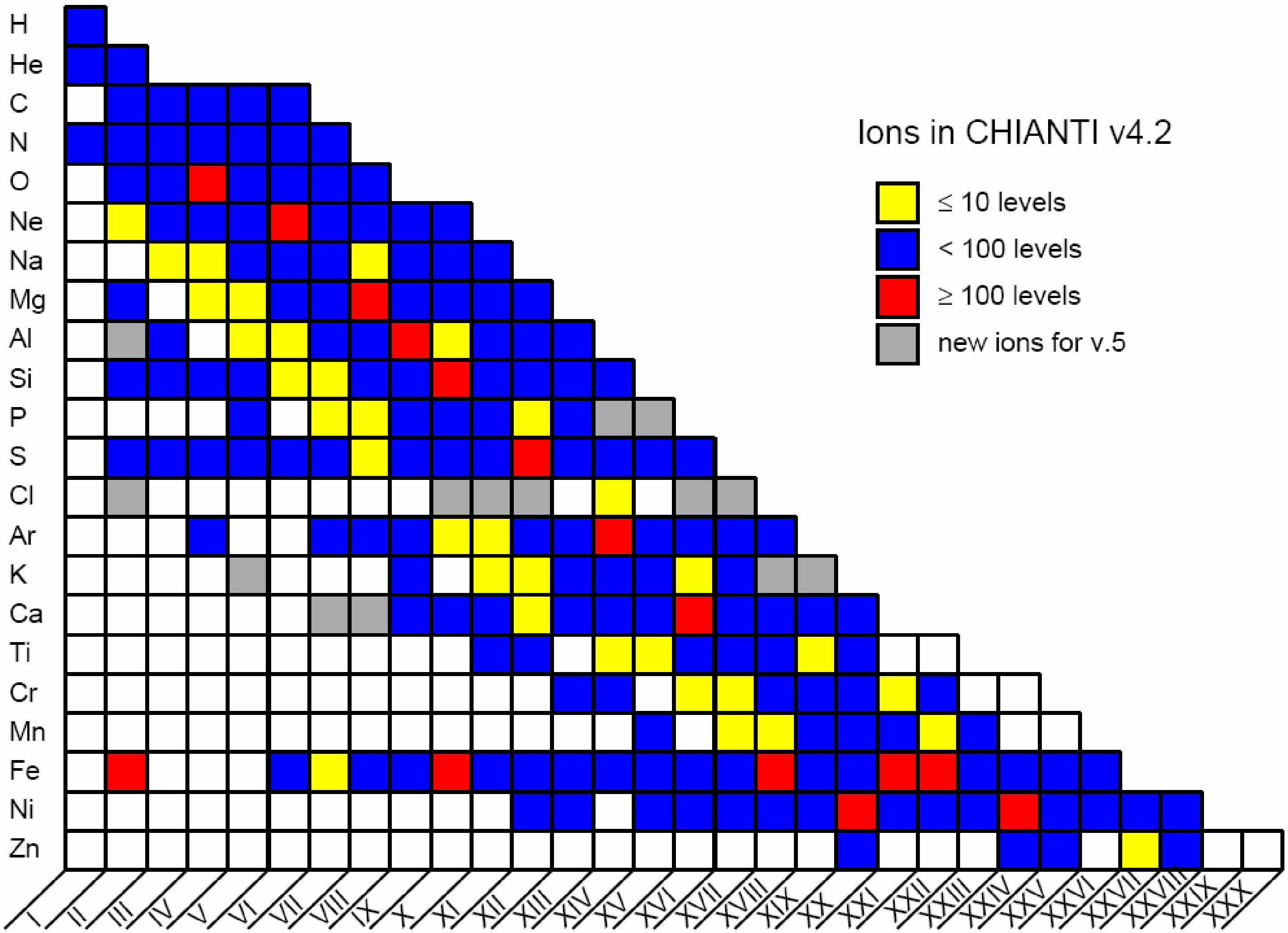
CHIANTI v.5

- Version 5 of CHIANTI will be released this summer

- Major improvements for iron at X-ray wavelengths
  - high-n levels for Fe XVII – XXIII
  - contribution of ionization/recombination to level balance
  - revised wavelengths
- Addition/improvements to existing ions
  - Fe VII, Fe IX, Fe X, Fe XII, Fe XXIII from IP
  - n=3 levels for C, N, O sequences
- New ions
  - Al II, Cl II, Cl X-XII, Cl XVI-XVII, P XIV-XV, Ca VII-VIII, K V, K XVIII-XIX

CHIANTI ion models



New data required

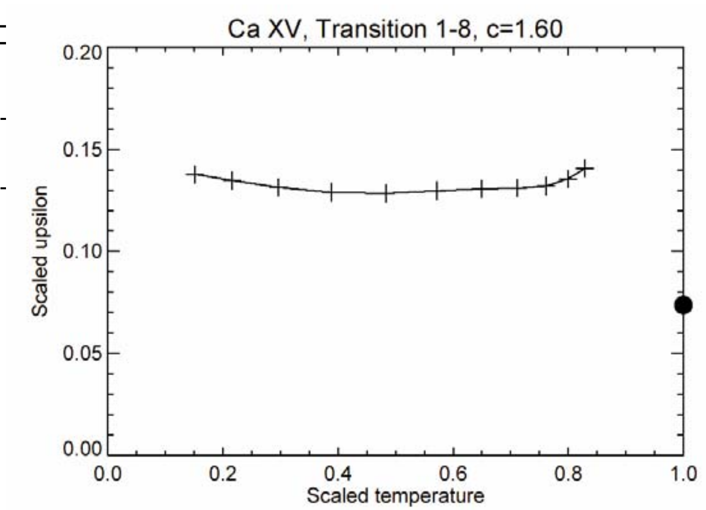
- Missing ions
  - low ionizations stages of S, Ar and Ca
  - neutrals
  - Mg III, Al IV (Ne-like)
- New data required
  - O-like ions (mainly n=2 models at present)
  - F-like ions (mainly 3 level models at present)

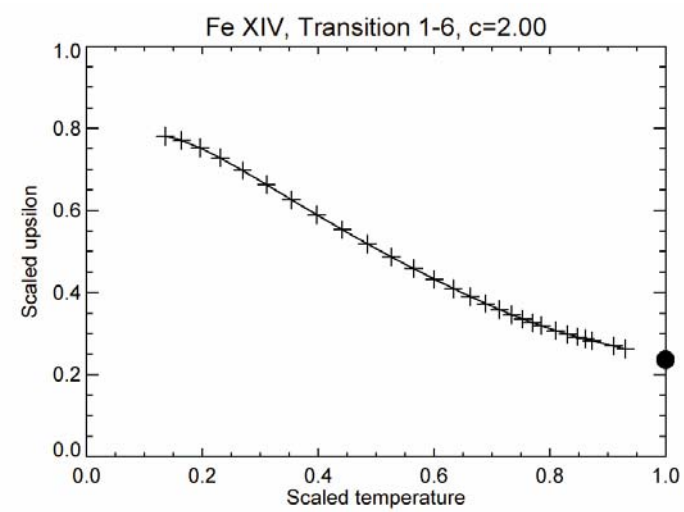
Oscillator strengths

- Intermediate Coupling oscillator strengths from collisional calculations are extremely valuable

- *High energy/temperature limit points*
  - very useful for checking allowed transitions

- *F … nco*
  - … l ca





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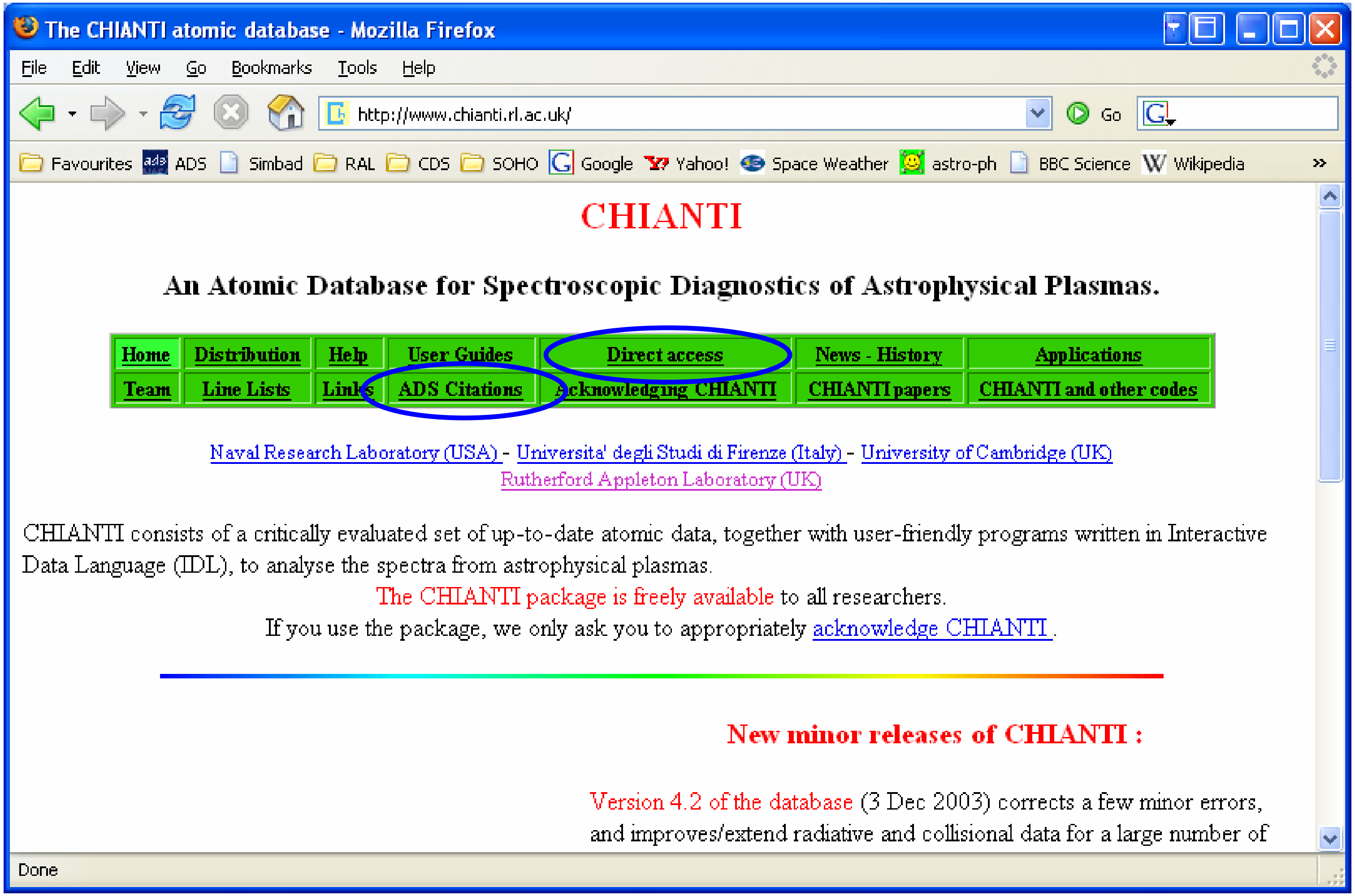
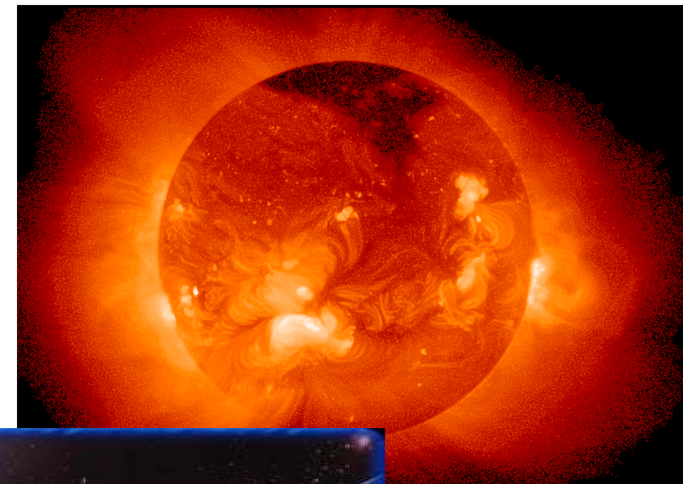
CHIANTI webpage



Solar-B

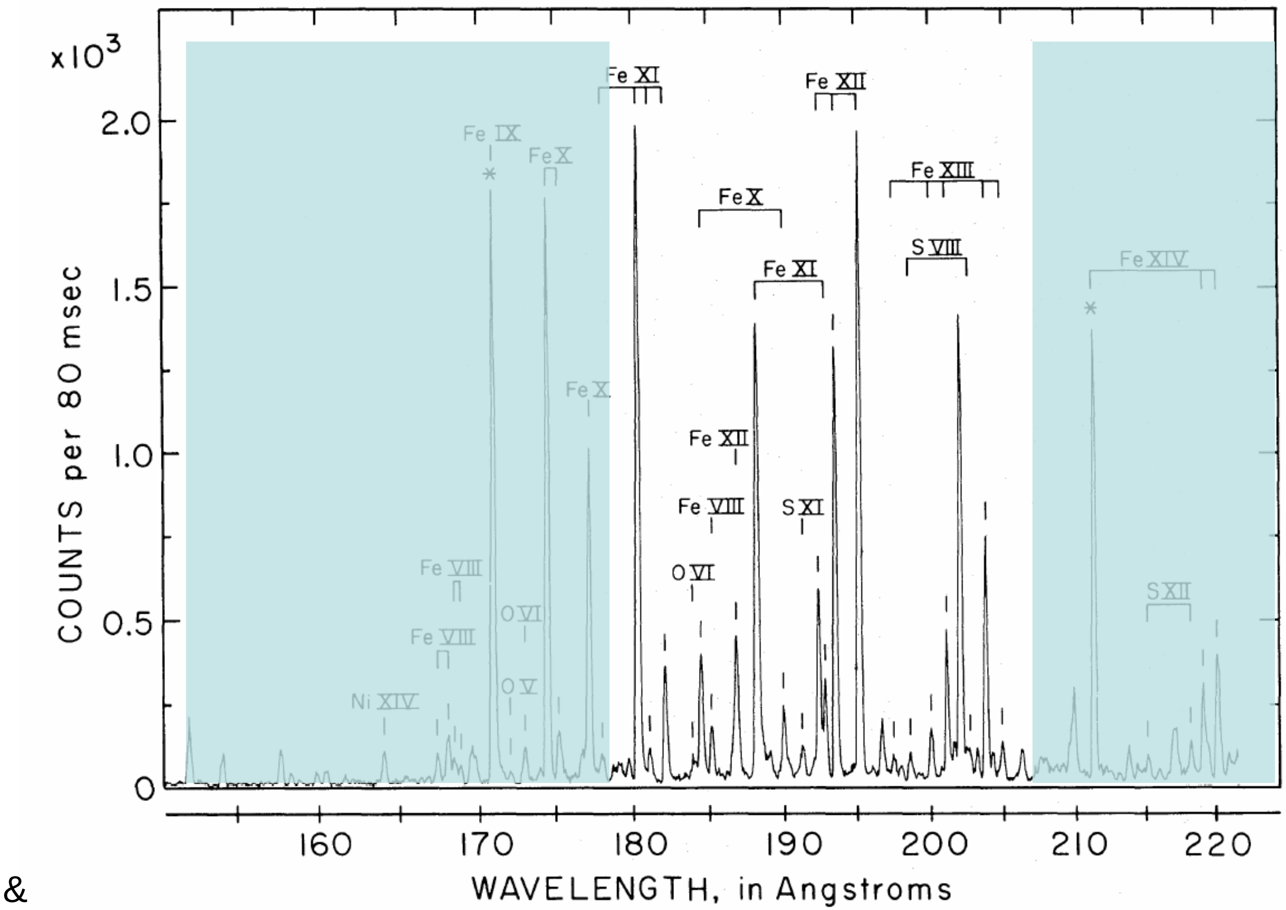
- Japan/US/UK/Norway mission
  - successor to *Yokkoh*
  - to be launched 2006
- 3 scientific instruments
  - EUV spectrometer [led by UK]
  - broad-band X-ray imager
  - optical telescope



Solar-B / EIS

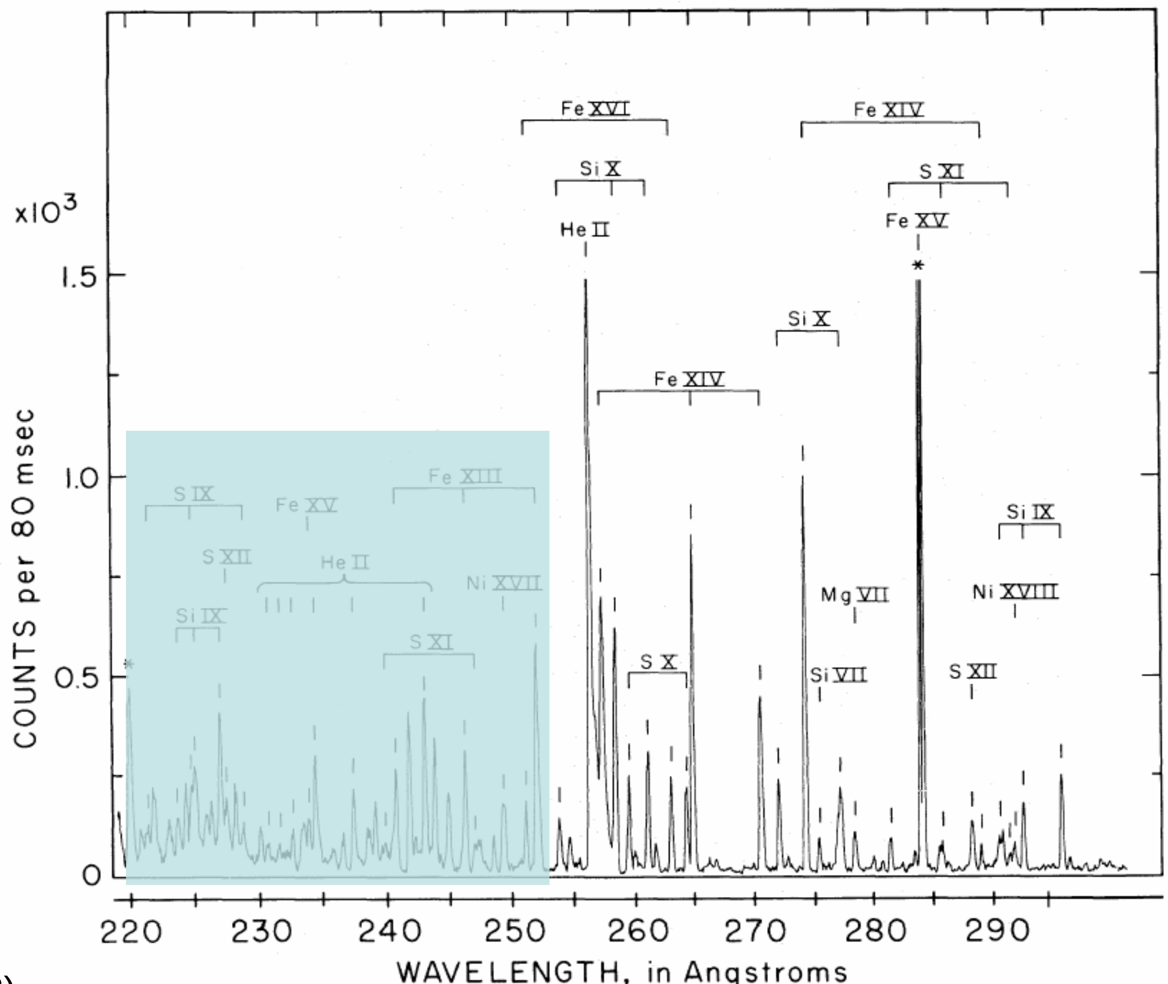
- High resolution spectra in two wavelength ranges
  - 170-210 Å
  - 250-290 Å
- Dominated by iron ions
  - Fe VIII, X-XVI, XXIII, XXIV
- Key density diagnostics
  - Fe XIII 203.8/202.0
  - Fe XII 186.9/195.1
  - Fe XIV 264.8/274.2

EIS: 170-210 Å band



Malinovsky & Heroux (1973)

EIS: 250-290 Å band



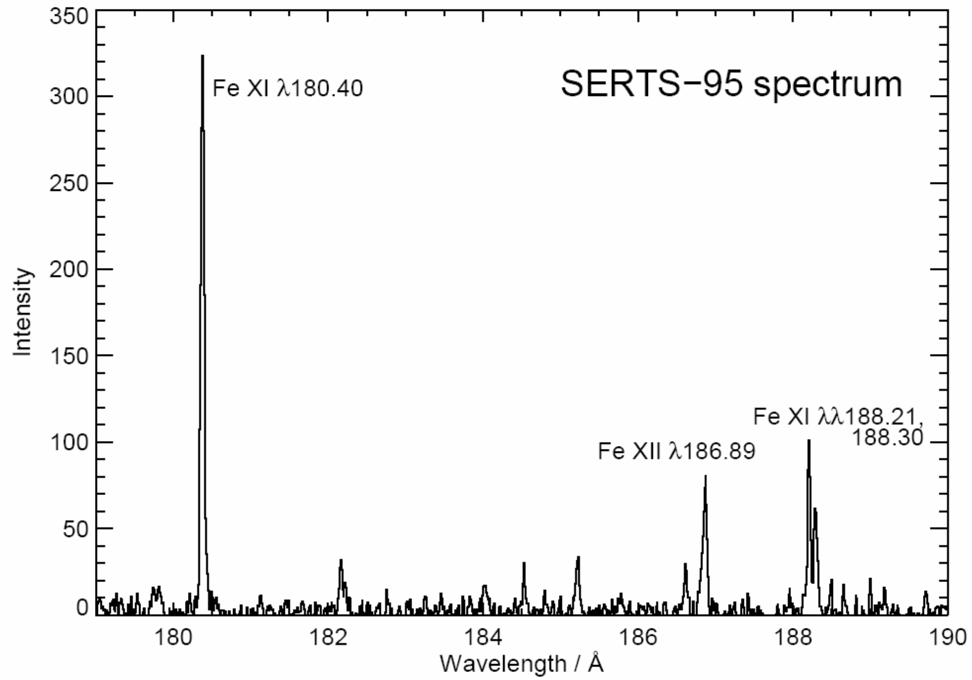
Malinovsky & Heroux (1973)

EIS data needs

- Iron ions: Fe XI, Fe XIII
  - no IP data available yet
- Cool ions: Mg V, Mg VII, Si VII
  - R-matrix for O-like ground configuration, but only to 10^5 K
  - no R-matrix data for Mg VII
- Ca XVII
  - flare line 192.82 (log T=6.7)
  - old R-matrix data from Dufton et al. (1983)
- Ni XVI
  - λ191.40/λ194.40 is a good density diagnostic for flare plasma (logT=6.5)
  - DW data from Bhatia & Doschek (1999)

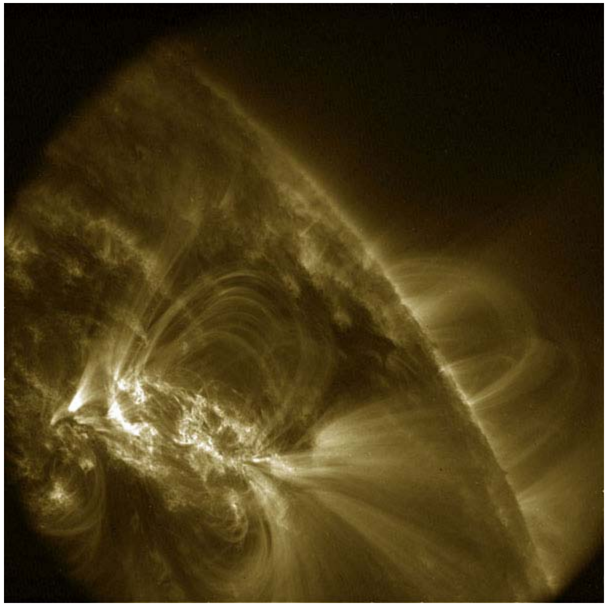
Fe XI problems

- Only 12 of 28 levels in $3s^2 3p^3 3d$ have observed energies
- Identification for one of strongest lines (λ188.30) is uncertain
  - Bhatia & Doschek (1996) data suggest $^1P_1$ upper level
  - Aggarwal & Keenan (2003) data suggest $^3S_1$



Solar Dynamics Observatory

- SDO
  - NASA mission
  - UK providing cameras (RAL) and data-processing algorithms (e-SDO project)
  - to be launched 2008
- High data rate will lead to ≈ 8 hi-res images every 10 seconds
- 3 instruments
  - *AIA*: UV/EUV imaging
  - *HMI*: visible, magnetograms
  - *EVE*: UV irradiance
- No spectroscopy!



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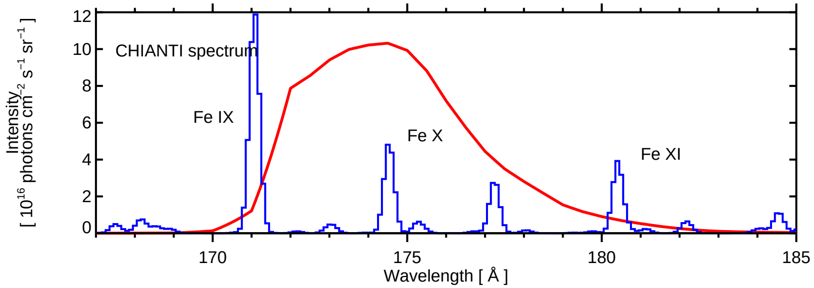
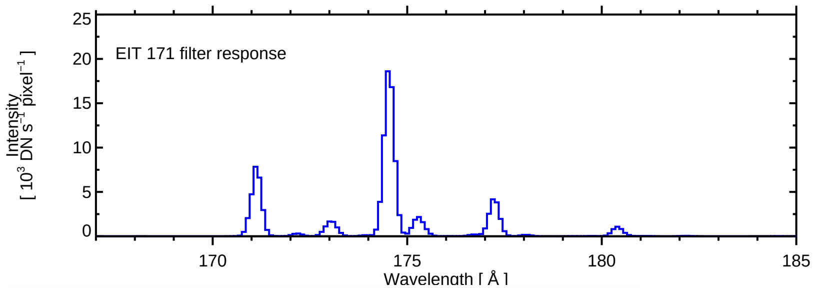
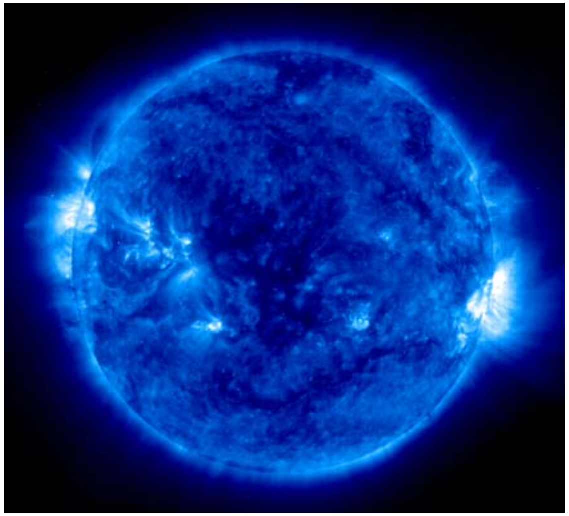
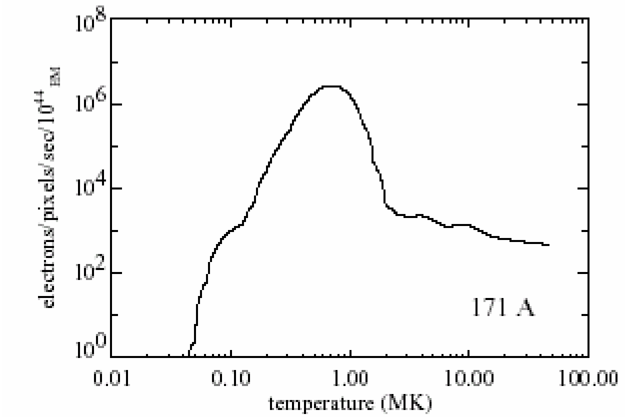
SDO imager

- Multilayer technology allows narrow band imaging in EUV









SDO – AIA instrument

- AIA filters:

Ion	Wavelength / Å	Log (*T*/K)
Fe IX / X	171	5.9
Fe XII / XXIV	195	6.1, 7.3
Fe XIV	211	6.3
Fe XVI	335	6.4
Fe XVIII	94	6.8
Fe XX / XXIII	131	7.0, 7.2

- Iron very important!

CHIANTI projects

- The CHIANTI team are actively involved in assessing and developing new atomic data

- E. Landi working with A. Bhatia to provide DW data where no other data available
- E.Landi working with M.F. Gu to calculate high-n iron line data
- G. Del Zanna, H. Mason, P. Young working with IP and RmaX groups

n=3 for C, N, O sequences

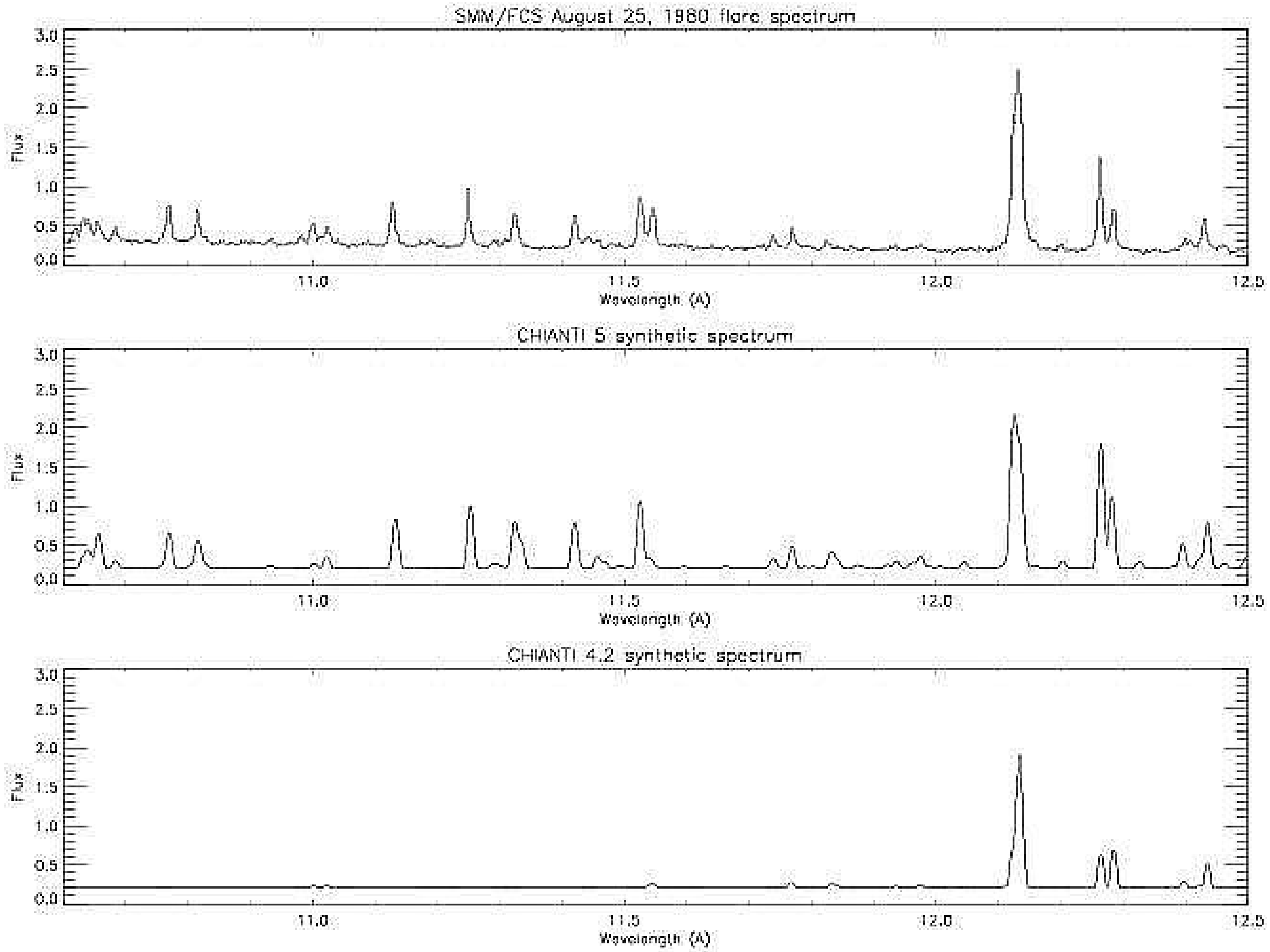
- A large number of n=3 to n=3 transitions are found in the UV, and have been seen by the SUMER instrument on SOHO
- Distorted wave data have been calculated for many ions by Bhatia & Landi
- C sequence
  - S XI
- N sequence
  - Mg VI, S X, Ar XII, Ca XIV
- O sequence
  - Ne III, Mg V, Si VII, S IX, Ar XI, Ca XIII

λ (Å)	Transition	Intensity	Comments
713.86	$(^2D)3s\,^1D_2-(^2P)3p\,^1D_2$	0.48	BL: Ar VIII
868.13	$(^2D)3s\,^3D_3-(^2P)3p\,^3P_2$	0.252	BL: Mg VII
902.24	$(^4S)3p\,^5P_1-(^4S)3d\,^5D_2$	0.023	
904.88	$(^4S)3p\,^5P_2-(^4S)3d\,^5D_{2,3}$	0.078	
906.99	$(^4S)3p\,^5P_1-(^4S)3d\,^3F_4$	0.015	
909.43	$(^4S)3p\,^5P_3-(^4S)3d\,^5D_{3,4}$	0.078	
915.10	$(^2D)3p\,^3F_3-(^2D)3d\,^3G_4$	0.038	
918.71	$(^2D)3p\,^3F_4-(^2D)3d\,^3G_5$	0.055	
963.94	$(^2D)3p\,^3F_4-(^2D)3d\,^3F_4$	0.0055	BL: Fe III, N I
967.19	$(^2D)3p\,^3F_2-(^2D)3d\,^3F_3$	0.012	BL: Fe III
968.42	$(^2D)3p\,^3F_2-(^2D)3d\,^3F_2$	0.025	
	$(^2P)3s\,^1P_1-(^2P)3p\,^1D_2$		
1005.54	$(^2P)3s\,^3P_1-(^2P)3p\,^3P_2$	0.029	BL: Ne VI
1006.24	$(^2P)3s\,^3P_2-(^2P)3p\,^3P_1$	0.025	
1009.91	$(^2P)3s\,^3P_2-(^2P)3p\,^3P_2$	0.098	
1132.80	$(^2P)3s\,^3D_3-(^2P)3p\,^3F_2$	0.125	
1135.39	$(^4S)3s\,^5S_2-(^4S)3p\,^3P_3$	0.53	
1137.24	$(^2D)3s\,^3D_2-(^2D)3p\,^3F_3$	0.081	
1141.68	$(^2D)3s\,^3D_1-(^2D)3p\,^3F_2$	0.014	
1142.46	$(^4S)3s\,^5S_2-(^4S)3p\,^5P_2$	0.25	
1143.55	$(^2P)3s\,^3P_2-(^2P)3p\,^3D_3$	0.15	
1146.54	$(^4S)3s\,^5S_2-(^4S)3p\,^5P_1$	0.079	
1167.72	$(^4S)3s\,^3S_1-(^4S)3p\,^3P_2$	0.086	
1169.30	$(^4S)3s\,^3S_2-(^4S)3p\,^3P_1$	0.046	
1199.52	$(^2P)3s\,^1P_1-(^2P)3p\,^1P_1$	0.14	BL: N I
1232.55	$(^2D)3s\,^3D_2-(^2D)3p\,^3D_2$	0.35	
1236.00	$(^2D)3s\,^1D_1-(^2D)3p\,^1F_3$	0.061	
1049.27	$2s^22p^4\,^3P_1-2s^22p^4\,^1S_0$	0.215	

FAC calculations

- Ming-Feng Gu developed the Flexible Atomic Code (FAC) based on HULLAC code
- Suitable for calculating collision data for high-n (n=3,4,5) for which no other data are available
- v.5 of CHIANTI will contain FAC data for
  - Fe XVII [n=3,4,5,6,7]
  - Fe XVIII – XXIII [n=3,4,5]
- Resonances are included for transitions involving n=2 and n=3 using the *isolated resonance approximation*

Example of new FAC data



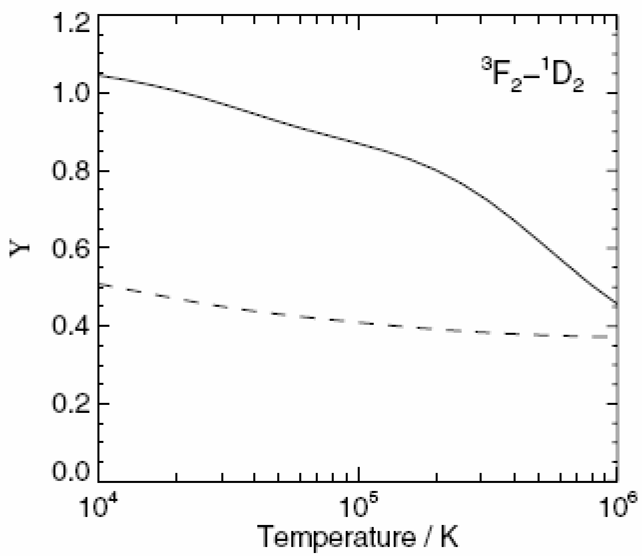
Benchmarking Fe data

- CHIANTI team are playing a key role in assessing quality of atomic data for iron ions
- Recent work

Fe VII	A-values, Upsilons	Young et al. (2005)
Fe X	Energies, A-values, Upsilons	Del Zanna et al. (2004)
Fe XII	Energies, A-values, Upsilons	Del Zanna & Mason (2005)
Fe XIII	A-values	Young (2004)
Fe XXIII	Energies, A-values, Upsilons	Del Zanna et al. (2005)

Fe VII

- Young, Berrington & Lobel (2005, A&A, 432, 665)



Upper level	Ratio	Observed	$E(B-V)$ 0.00	0.10
$^1S_0$	$\lambda2143^a/\lambda2016$	0.288 ± 0.054	0.242	0.224 ◁
	$\lambda2183/\lambda2016$	0.036 ± 0.007	0.038	0.036
$^1G_4$	$\lambda3587/\lambda3759$	0.663 ± 0.047	0.715	0.704
$^3P_2$	$\lambda4699/\lambda4943$	0.247 ± 0.017	0.226	0.221 ◁
	$\lambda5277^b/\lambda4943$	0.609 ± 0.045	0.988	1.017 ◀
$^3P_1$	$\lambda4894/\lambda5160^c$	0.553 ± 0.039	0.695	0.678 ◁
$^1D_2$	$\lambda5722/\lambda6088^d$	0.623 ± 0.044	0.656	0.642

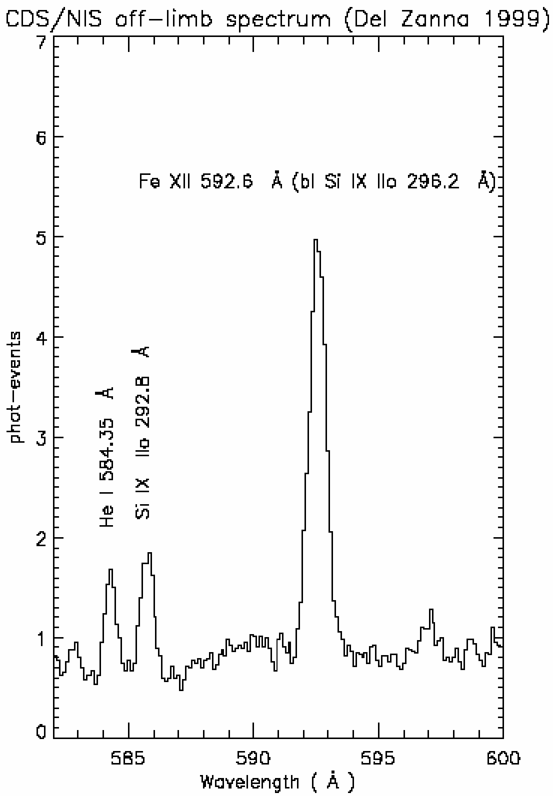
[a] Flux corrected for blend with N II $\lambda2143.452$.
[b] Flux corrected for blend with Fe II $\lambda5277.480$.
[c] Blended with Fe II $\lambda5160.214$ (not corrected).
[d] Flux corrected for blend with Ca V $\lambda6088.058$.

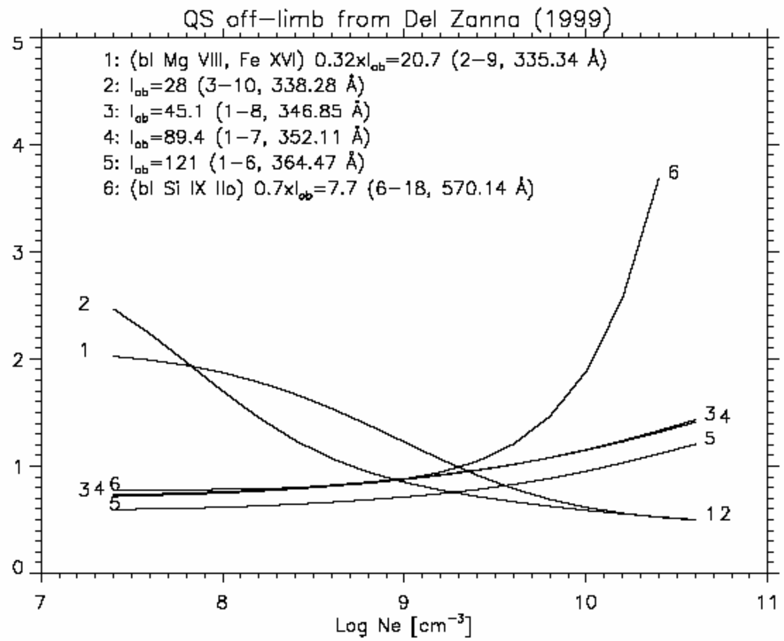
Table 4. Comparison of observed line ratios with those derived from the fitting procedure. The ratios are formed by summing lines from a common upper level, and comparing with the summed lines from the $^1D_2$ level.

Upper level	Ratio Observed	Fitted
$^3P_0$	0.043 ± 0.003	0.039
$^3P_1$	0.042 ± 0.003	0.042
$^3P_2$	0.170 ± 0.008	0.183
$^1G_4$	1.003 ± 0.051	1.016
$^1S_0$	0.064 ± 0.005	0.063

Fe XII

- Del Zanna & Mason (2005, A&A, 433, 731)





Neutrals

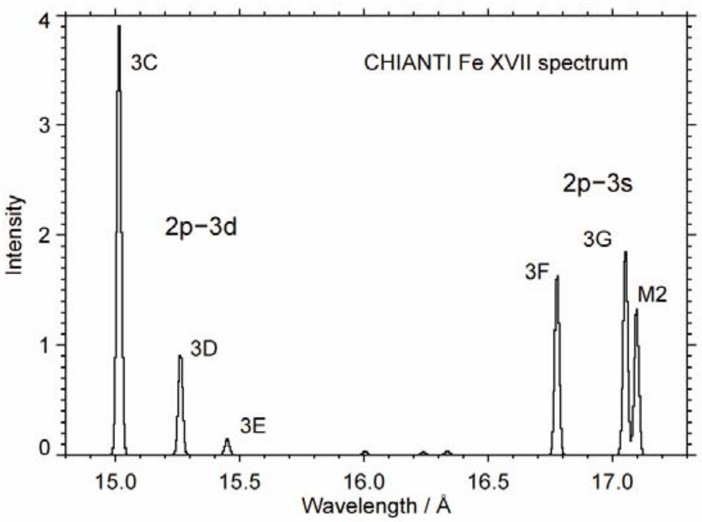
- Only neutrals currently in CHIANTI are H, He and N
- Data for sulphur and oxygen have been calculated by Tayal and collaborators, but only in LS-coupling
- IC data for following neutrals are needed
  - C I
  - O I
  - Ne I
  - Mg I
  - Si I
  - S I

Fe XVII

- Two key problems

1. observed (lab+astro) 3C/3D is less than theory prediction
2. observed 2p-3s/2p-3d ratios higher than theory

- Possible solutions include
  - recombination + cascading
  - resonances



Recombination & Ionization

- Ion balance calculations are generally recognised as the biggest source of uncertainty when interpreting spectra
- Updates to the ion fractions presented in Mazzotta et al. (1998) are urgently required

- A future version of CHIANTI (v6, v7?) will provide assessed ionization and recombination rates
- CHIANTI ion balance will be updated regularly

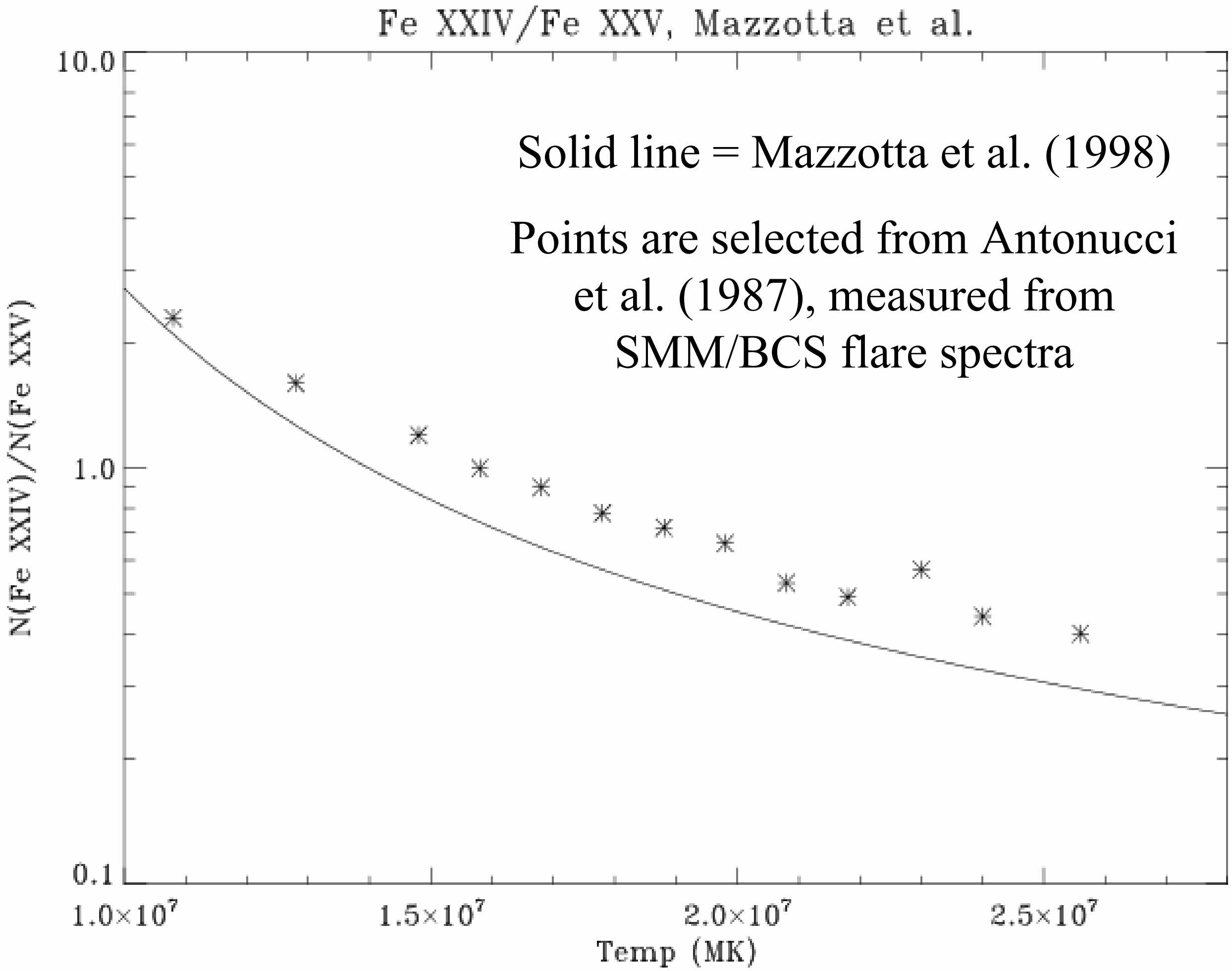
DR rates

Dielectronic Recombination data

B - Badnell et al.
G - Gu
N* - Nahar
M - Mazzotta et al.

	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI	XXVII
He	B																									
C	B	B	B	B	B																					
N	B	B	B	B	B	B																				
O	N*	B	B	B	B	B	B																			
Ne	B	B	M	B	B	B	B	B	B																	
Mg	G	B	B	B	B	B	B	B	B	B	B															
Al	M	G	B	B	B	B	B	B	B	B	B	B														
Si	N*	N*	G	B	B	M	B	B	B	B	B	B	B													
S	M	N*	N*	M	G	B	B	B	B	B	B	B	B	B	B											
Ar	M	M	M	M	N*	M	G	B	B	B	B	B	B	B	B	B	B									
Ca	M	M	M	M	M	M	N*	M	G	B	B	B	B	B	B	B	B	B	B							
Ti	M	M	M	M	M	M	M	M	M	M	G	B	B	B	B	B	B	B	B	B	B					
Cr	M	M	M	M	M	M	M	M	M	M	M	M	G	B	B	B	B	B	B	B	B	B	B			
Fe	N*	N*	N*	N*	N*	M	M	M	M	M	M	M	N*	M	G	B	B	B	B	B	B	B	B	B	B	
Ni	M	N*	M	M	M	M	M	M	M	M	M	M	M	M	M	M	G	B	B	B	B	B	B	B	B	B

Ion balance problems



Summary

- The Iron Project have done an excellent job in updating key iron ions
  - Fe IX, Fe X, Fe XII, Fe XIV
- New data for Fe XI, Fe XIII, Fe XVII are eagerly awaited
- Iron extremely important for future solar missions: Solar-B, SDO

- M-shell ion calculations for other elements also important (S, Ar, Ca)

- Some key L-shell ions need R-matrix calculations (Mg VII, O-like, F-like)

- Electron excitation calcs in good shape

  …but calcs for ionization & recombination urgently needed