Benchmarking Atomic data for Astrophysics

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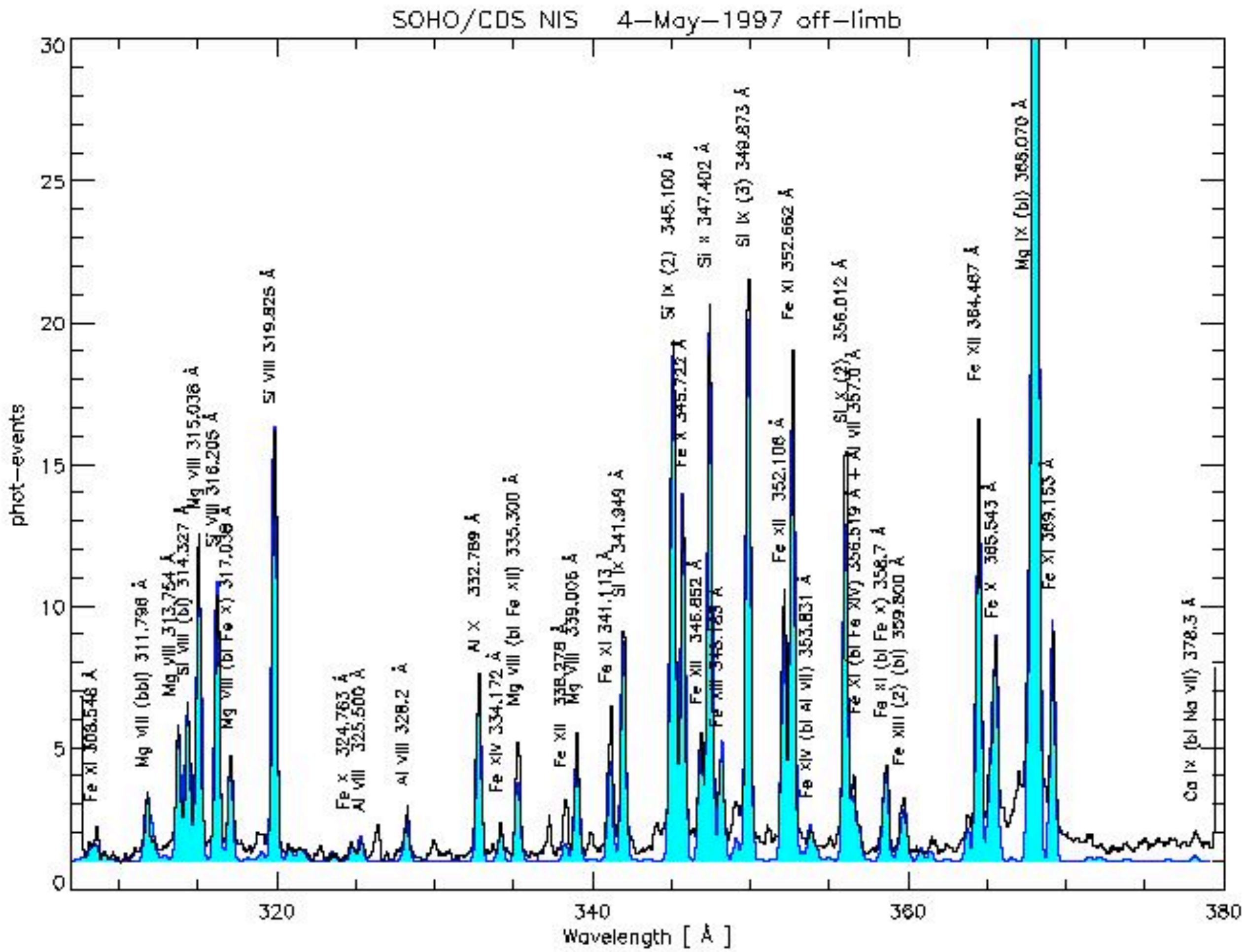
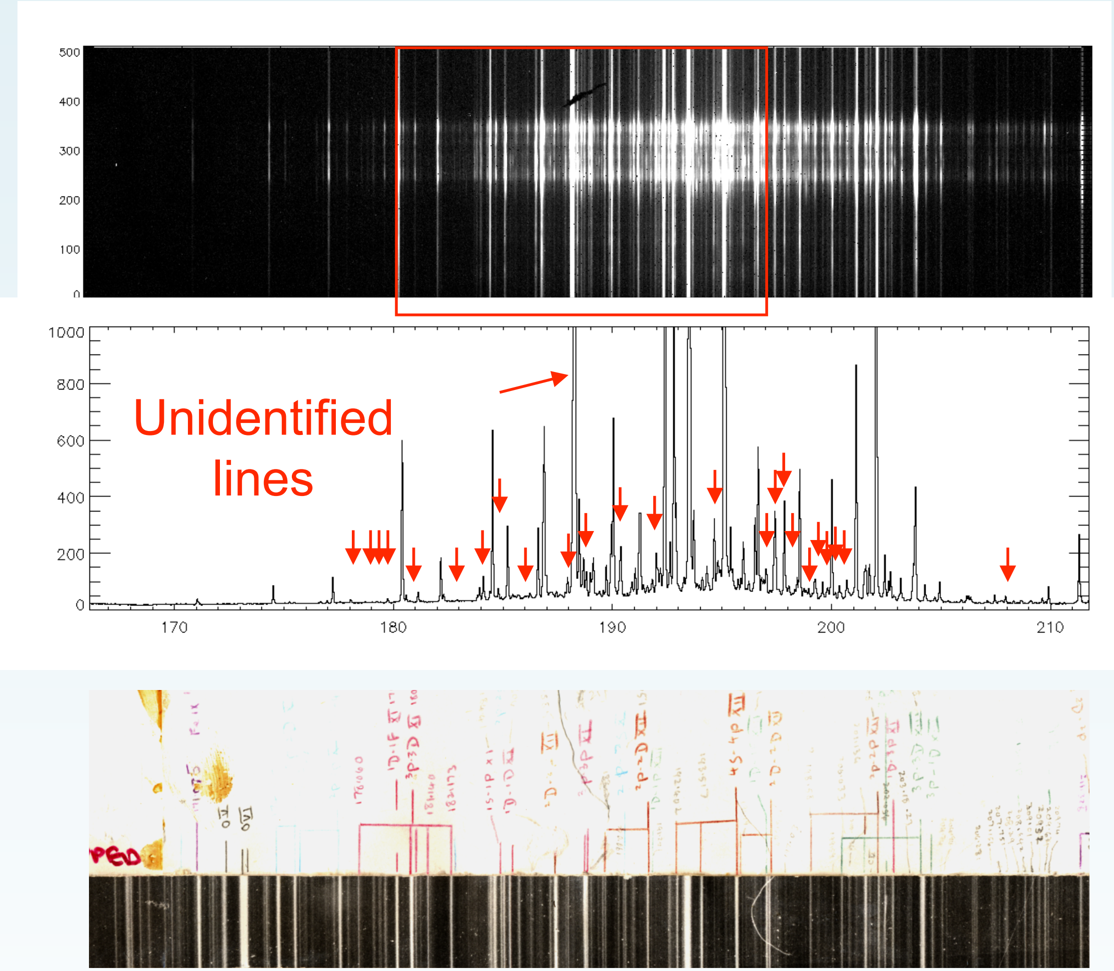
SOHO/CDS forward modeling

Black: observed solar spectrum (SOHO/CDS); blue: theoretical model spectrum



Del Zanna (1999)

Hinode EIS SW



Almost as good as B.Fawcett's plates.

B.Fawcett 166 – 212 Angstroms

SUPERSTRUCTURE

Werner
Eissner

Pete
Storey

Helen

Alberto Binello

```
 0-1 1 3   24555 14565 24545516 14555516
           65516 14545526 24535526 24545517 24545518
           24545519 2454551A 14555517 14555518 14555519
           1455551A 2454551B 2454551C 2454551D 2454551E
           1455551B 1455551C
00    0 0                                                                         00000000
  0  0 -4  0  0  0 11  0  0  0  0  0  0  0  0
   26    0   14    0    0    1    7    0
 31 31 31 31 31 31 31 31  0  0  0  0  0  1  0 21  0  0  0  0  0  0
  0
  1.4112  1.1205  1.0649  1.1556  1.1312  1.1387  1.1706  1.1399  1.1534
  1.2947  1.1796  1.1502  1.1588  1.2832
  1  2  3  4  5  6  7  8  9 10 11 12 13 14
```

Benchmarking atomic data for astrophysics

A novel approach: atomic structure (and occasionally R-matrix scattering) calculations with comparisons between

1) observed and theoretical wavelengths;
2) line intensities for a wide range of astrophysical and laboratory plasmas using the emissivity ratios (follows one idea from Brunella):

$$F_{ji}(N_e, T_e) = C \; \frac{I_{ob} N_e}{N_j(N_e, T_e)\, A_{ji}}$$

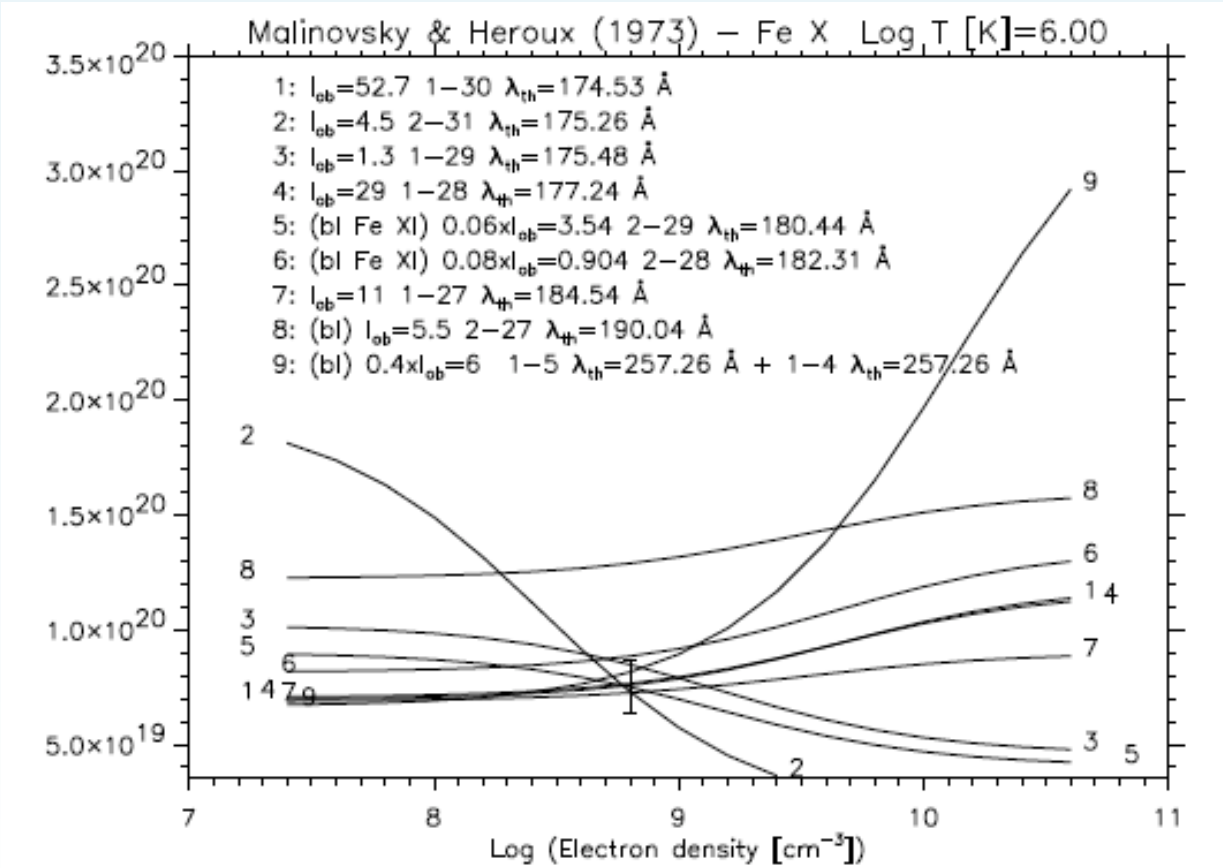
Result: a large number of revised wavelengths (with uncertainties), new identifications, new level energies and new diagnostic applications.

Appropriate references !

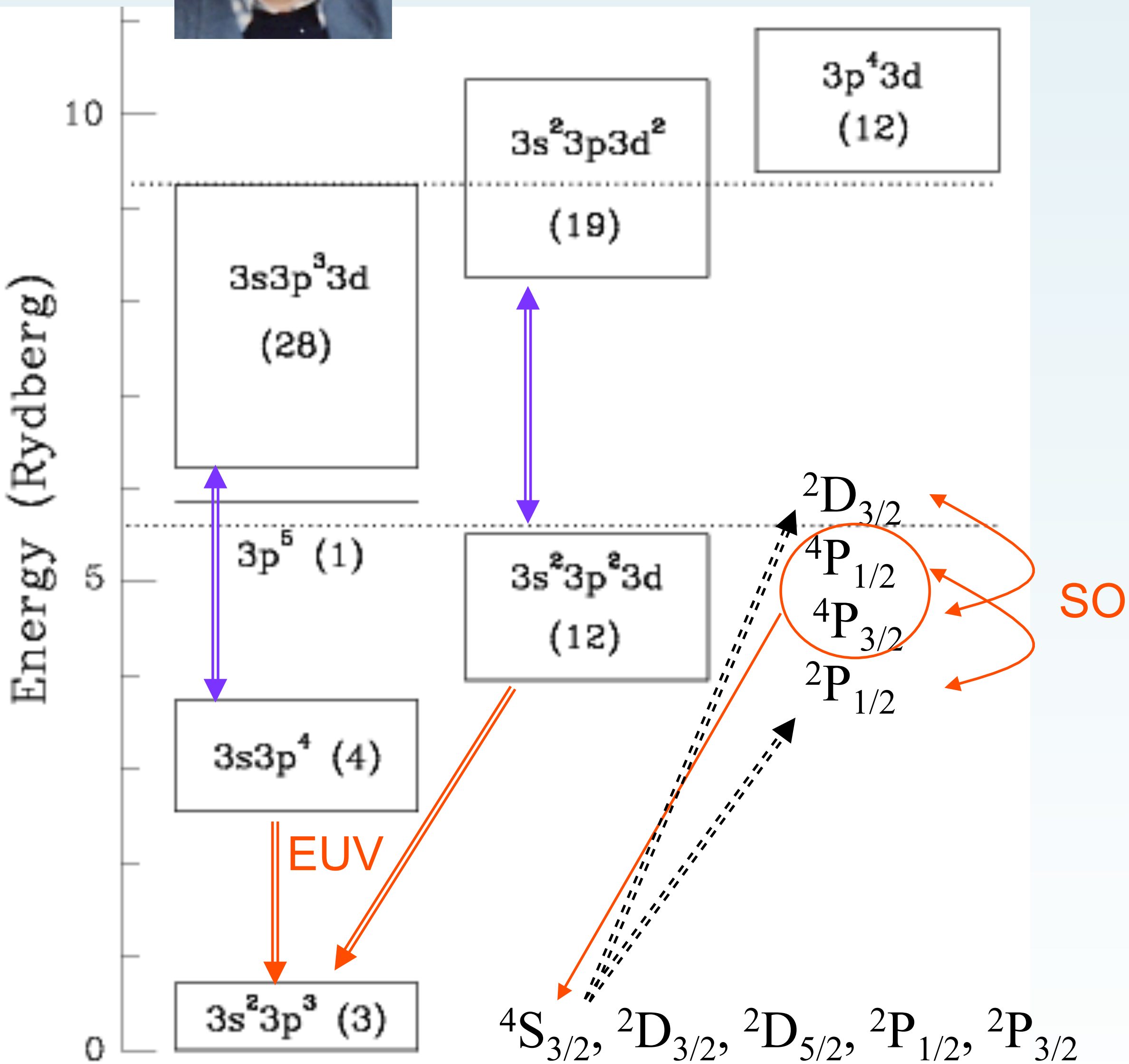
Typically, one ion in 2-5 years..

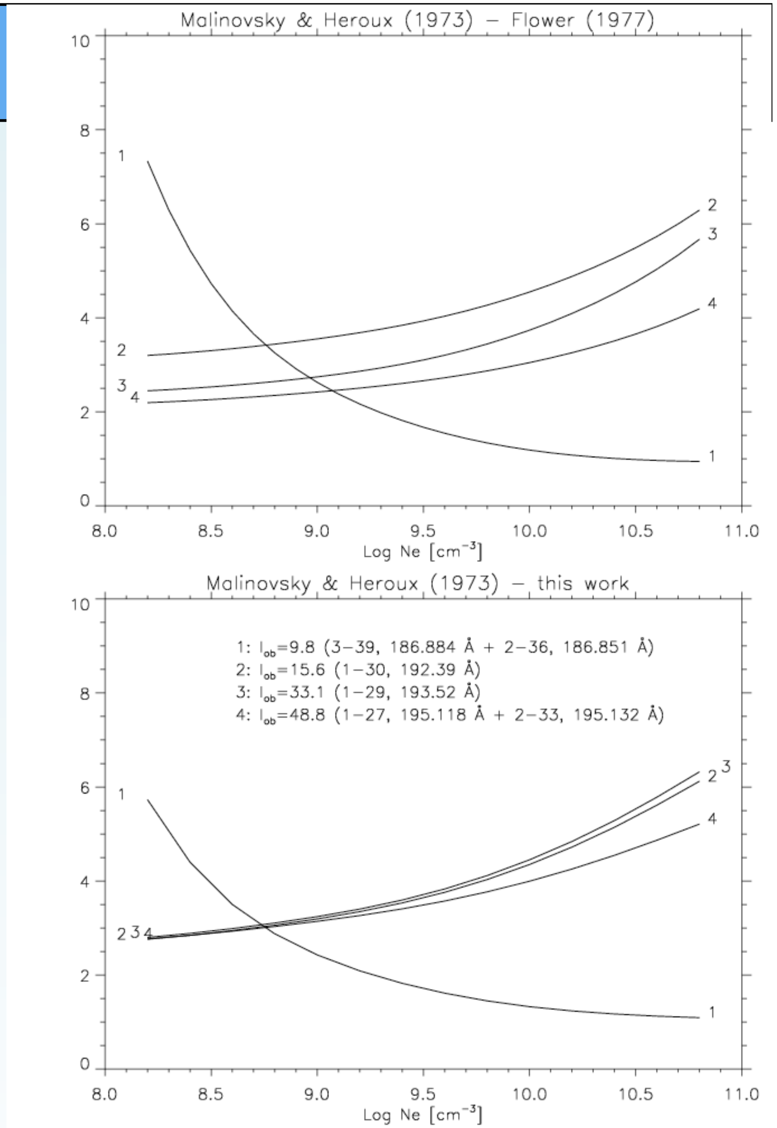
Fe X

Del Zanna, Berrington, Mason (2004)



Fe XII





From Flower (1977) until Storey et al. (2005) serious problems. Solved ?

Fe XII

21/58 new transitions identified/revised

(Del Zanna & Mason 2005)

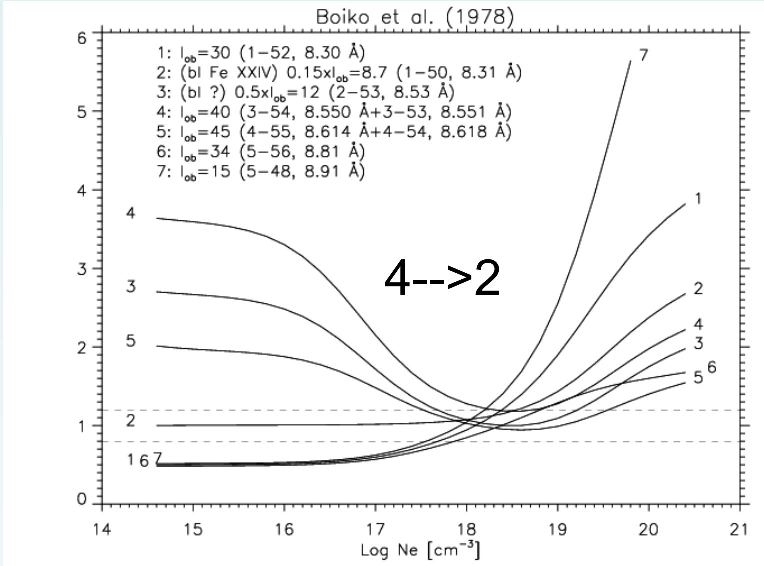
λ_{best} (Å)	$\lambda_{observed}$ (Å)	Same ID	Diff. ID	
179.259±0.007	179.266±0.01 U	B78		H
186.241±0.003	186.248±0.01 U			H,N
186.854±0.004	186.854±0.002 (B78, bl mr)	B78		
186.887±0.007	186.887±0.005 (U, bl mr)	G66, B78		H,N
188.170±0.018	188.17±0.01 U		B78 (188.216)	H,N
188.450±0.004				
190.068±0.004	190.06±0.01 B78	B78		H
190.467±0.018	190.459±0.01 B78	B78		H
191.007±0.184				
191.049±0.008	191.049±0.01 U	F71		H
192.394±0.002	192.394±0.002	F67		
193.204±0.188				
193.509±0.002	193.509±0.002	F67		
194.903±0.002	? 194.92±0.01 B78			H
195.119±0.002	195.119±0.002 (bl mr)	F67		
195.179±0.002	195.179±0.002 (U, bl mr)			H,N
196.640±0.002	196.640±0.01 (bl mr Fe XIII)	B78		
196.921±0.002	196.923±0.01 B78	B78		H
198.581±0.008	198.58±0.01 U		B78	H,N
201.140±0.008	201.15±0.01 U		B78	H,N
201.740±0.021	201.75±0.01 U			H,N
201.760±0.009	201.75±0.01 U			H,N
203.728±0.005	203.728±0.004 (bl Fe XIII mr)		B78 (203.272)	N
206.368±0.005	? 206.369±0.01 (bl ?)	B78		
208.316±0.005	? 208.318±0.01 B78 (bl ?)	B78		H
208.421±0.003				
209.113±0.003	-			
210.918±0.003	? 210.932±0.01 B78	B78		H
211.732±0.005	? 211.738±0.01	F71		H
214.399±0.003	214.405±0.01			
217.276±0.015	? 217.271±0.01	F71		H
219.095±0.005				
219.437±0.015	219.438±0.004 (bl ?)	F71		
221.410±0.049	221.41±0.01 (bl S XII)			N
223.000±0.100	223.0±0.2 (? T02)			H
223.179±0.249				
225.572±0.254	? 225.856±0.004 (bl)			N
227.406±0.006				
230.768±0.006	? 230.78±0.01 U	B78		H
232.149±0.054				
237.369±0.017				
240.740±0.059	240.74 U (bl 240.713 Fe XIII)			N
246.421±0.321				
248.767±0.310				
249.388±0.032	249.388±0.01 (bl ?)			N
251.868±0.020				
256.410±0.066	256.41±0.01 U (bl Fe XIII)			N
259.495±0.068	? 259.494±0.002 (bl S X)			N
259.963±0.068	? 259.963±0.002 (bl S X ?)			N
283.443±0.017	283.446±0.008 (J93)	F71(283.64),J93		H
287.221±0.017	287.226 J93	J93		H
291.010±0.018	291.01±0.01 (bl Fe XIV)	F71		
303.135±0.019	? 303.135±0.008 (J93)	J93		H
312.253±0.020	? 312.255±0.008 (J93)	J93		H
323.411±0.022				
332.925±1.105				
335.380±0.035	335.38±0.01 (U, bl Fe XVI, Mg VIII)	J93	F71 (335.06)	R
336.979±0.623				
338.263±0.013	338.263±0.01	F70(338.27)		
346.852±0.006	346.852±0.01	F71		
352.106±0.006	352.107±0.01	F71		
363.792±0.700				
364.467±0.007	364.467±0.004	F71		
376.481±0.044				
382.847±0.016	382.83±0.01 (F71)	F71		H
439.589±1.156				
592.600±0.123	592.6±0.1 D99			N
607.168±1.948				
661.967±2.206				
1242.01±0.01	1242.00±0.01 (SBT77, bl ?)	BRW67		
1349.40±0.02	1349.40±0.01 (SBT77)	BRW67		
1847.23±11.19	? bl 1847.25 (SBT77)			N
2169.76±0.05	2169.08±0.02 (SBT77, air; 2169.76 vacuum, bl Ni III)	G71,J71,S71		
2406.41±0.06	2405.68±0.01 (SBT77, air; 2406.41 vacuum, bl Fe II)	SBT77		
2566.77±0.13	2565.93±0.06 (SBT77, air; 2566.70 vacuum, bl Fe II,?)	SBT77		
2904.70±0.17	-			
3072.06±0.19	3072. (Je71 air; 3072.9 vacuum)	J71,S71		

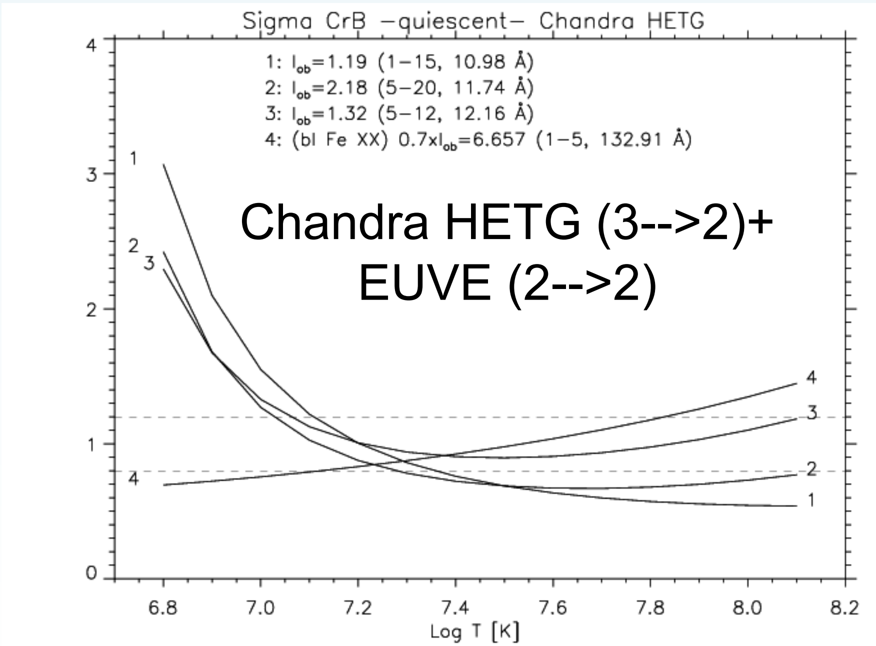
R-matrix and Fe XXIII 1 year !

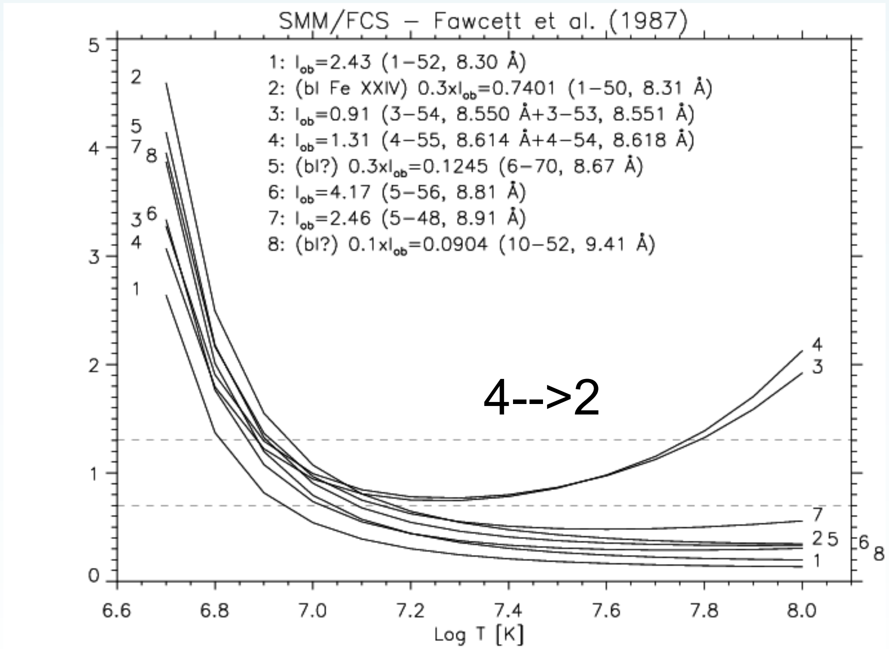
New electron impact excitation by Chidichimo et al. (2005).

Del Zanna et al. (2005):

New diagnostics to measure electron temperatures and densities.



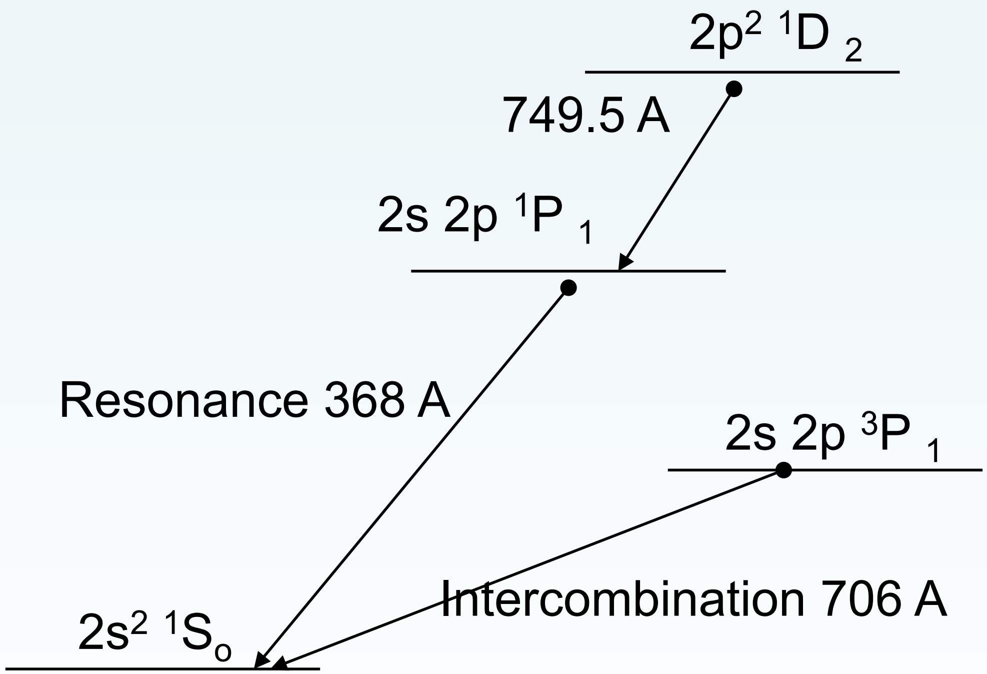


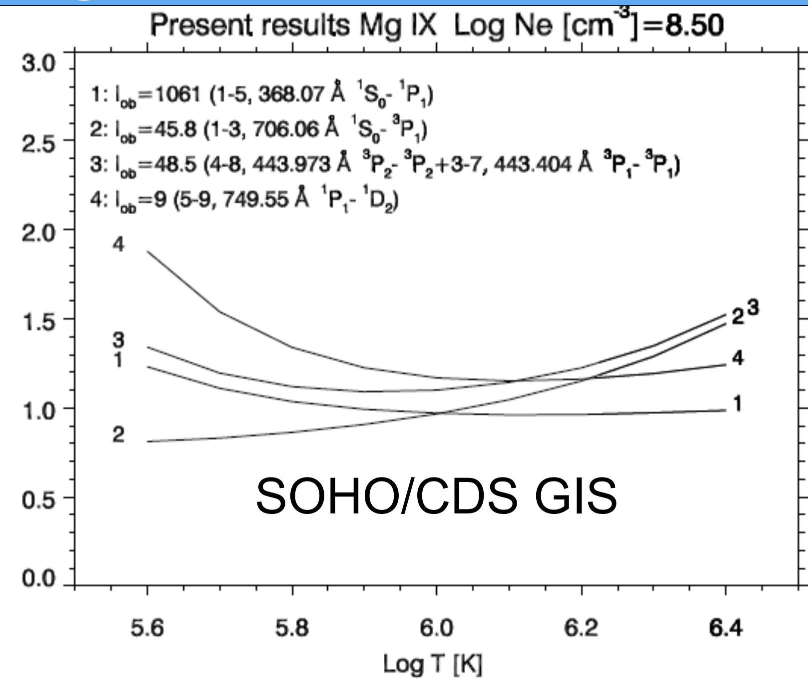


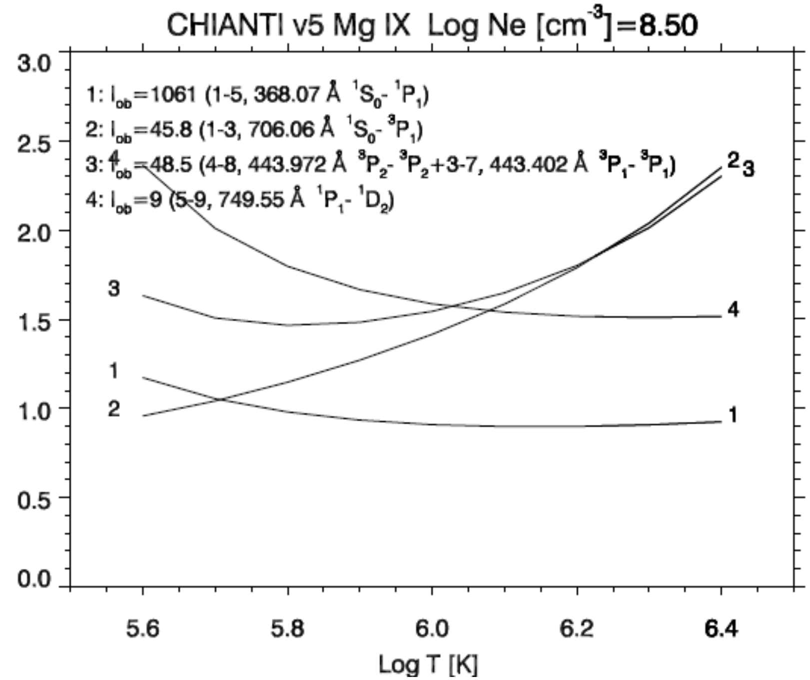
Be-like Mg IX: 1 year

First R-matrix calculation for Be-like Mg (Del Zanna Rozum Badnell 2008) resolved significant problems.

Best Te diagnostic for the 1 MK corona.
Te in CH underestimated by a factor of 2

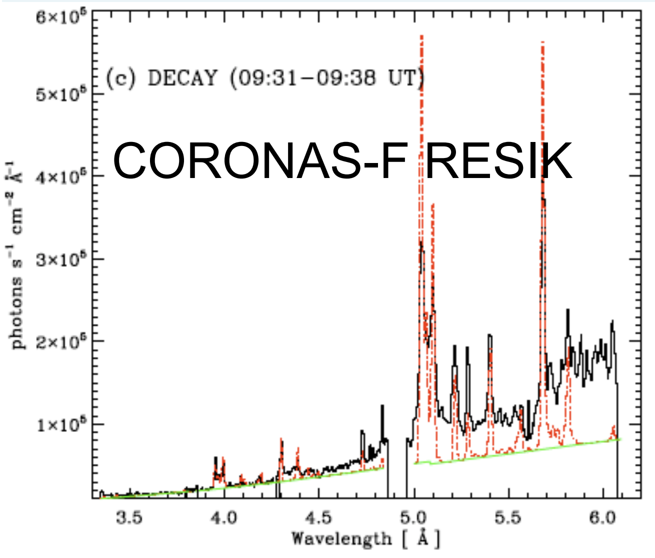


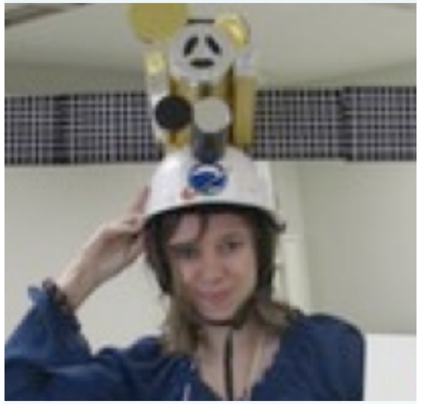




Preliminary benchmarks for the X-rays

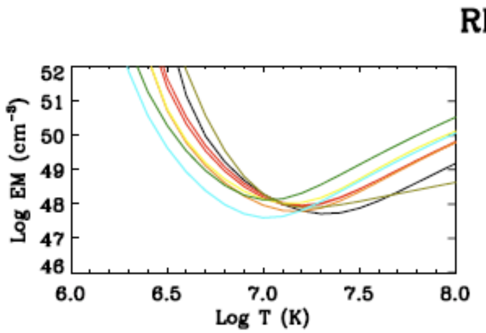
A lot of benchmark work went into the preparation of CHIANTI v.4, released in 2003 (e.g. Del Zanna G. 2002) and for v.5 (cf. Chifor, Del Zanna et al. 2007).
Significant work still needed.

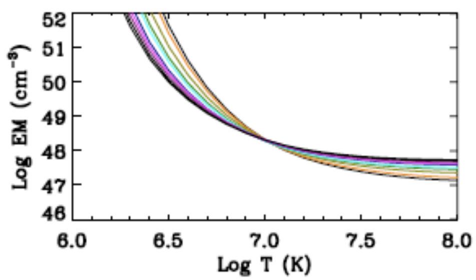


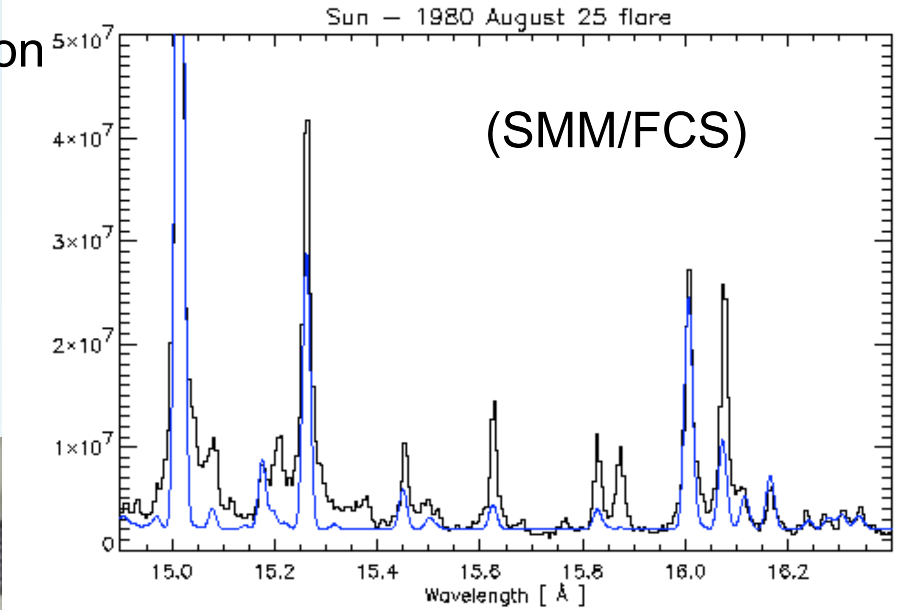


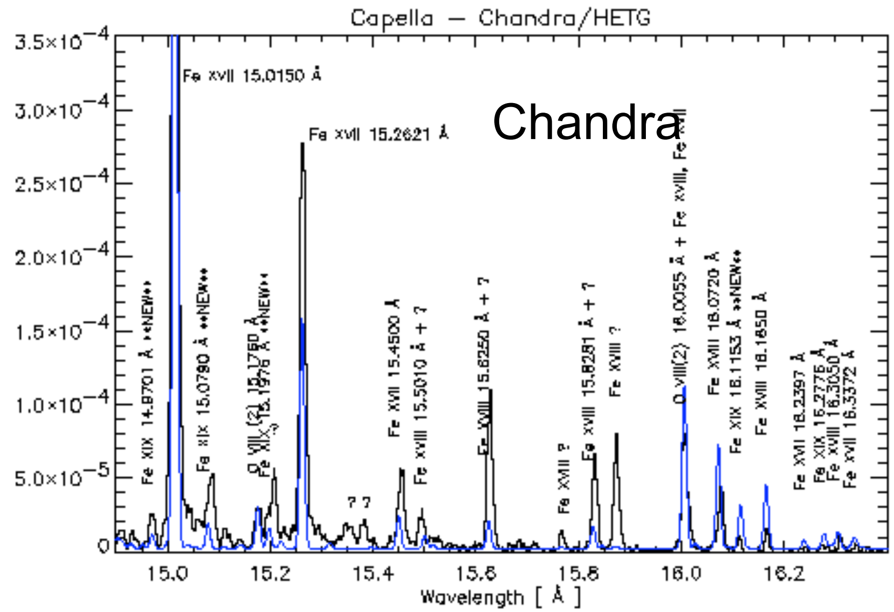
EM lines

EM continuum

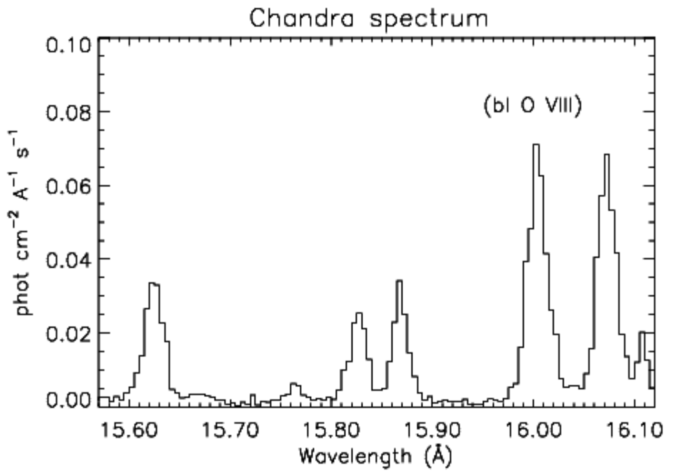


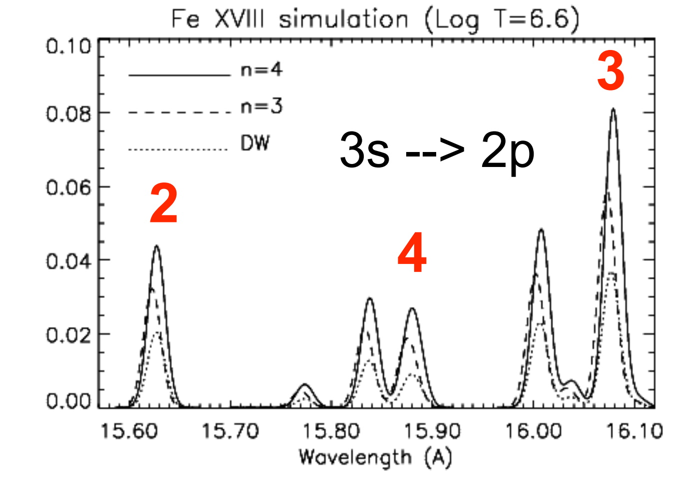




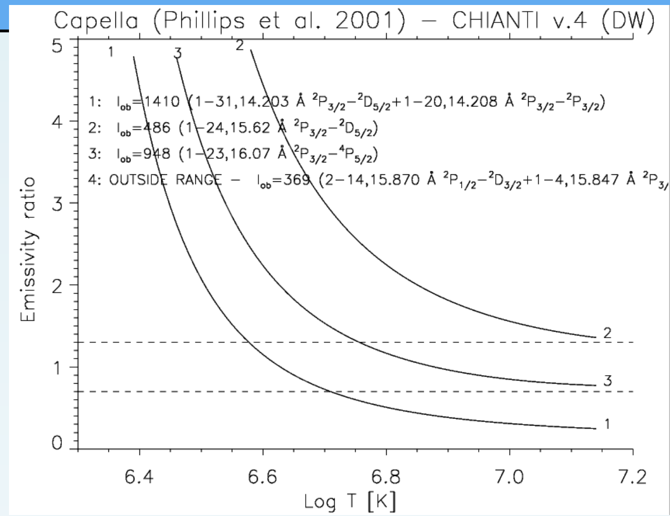


R-matrix ! Fe XVIII

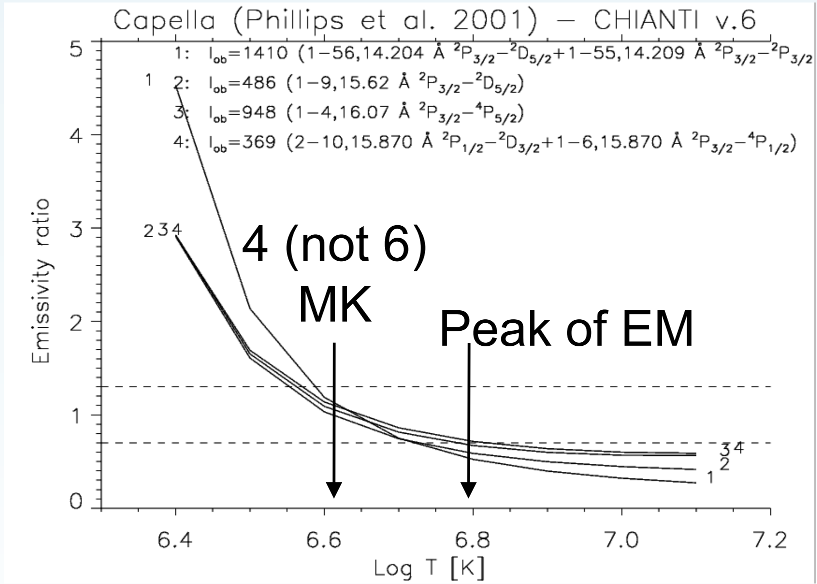


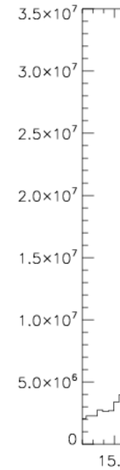


DW:



R-matrix:



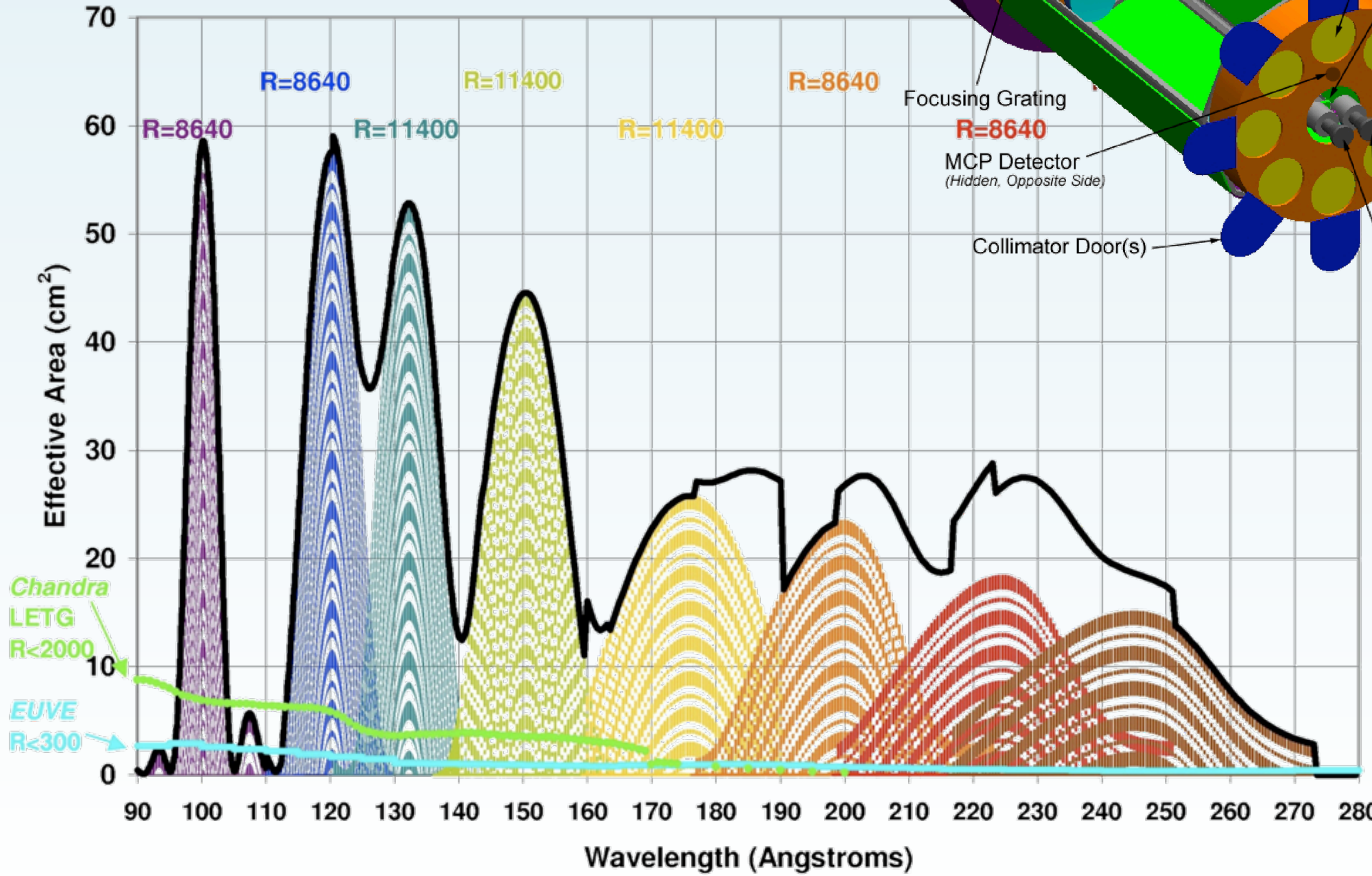


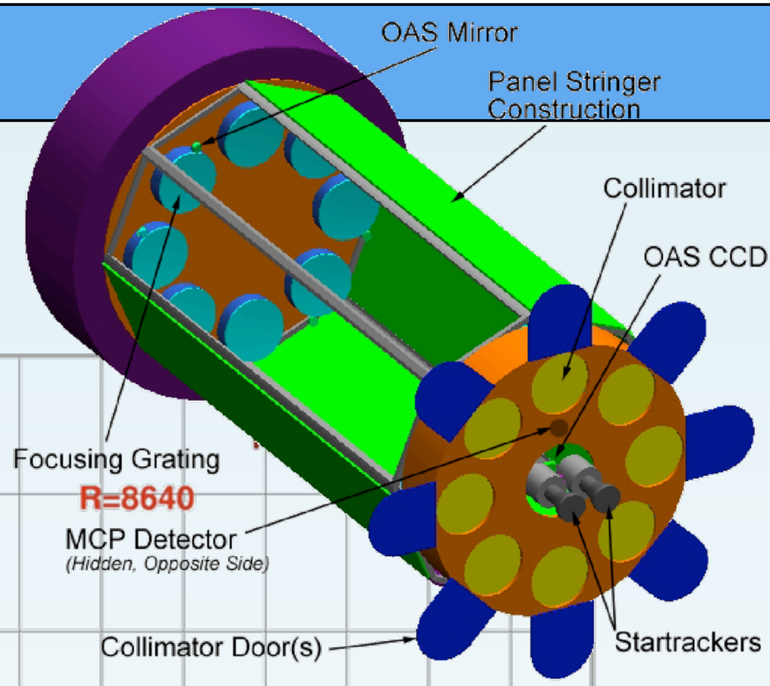
The large discrepancies for the strong 3s--> 2p transitions have been resolved with the first R-matrix e- scattering calculation by Witthoeft, Badnell, Del Zanna et al. (2006).

New diagnostics to measure electron temperatures and densities (Del Zanna 2006). Same issues with Fe XVII. In 30 years dozen of papers with speculations…

SAGE (ESA CV)

Consortium 6 ESA nations (M.Barstow)
J-PEX Spectrometer (NRL)

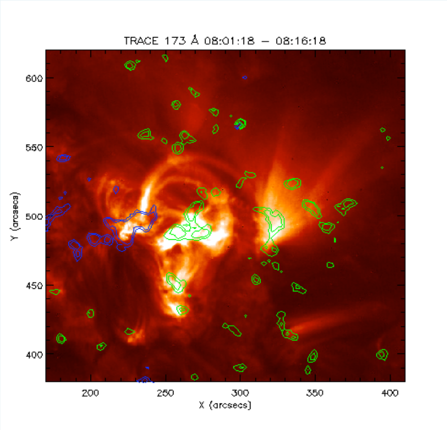


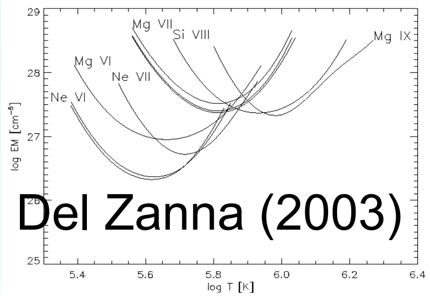


EM loci

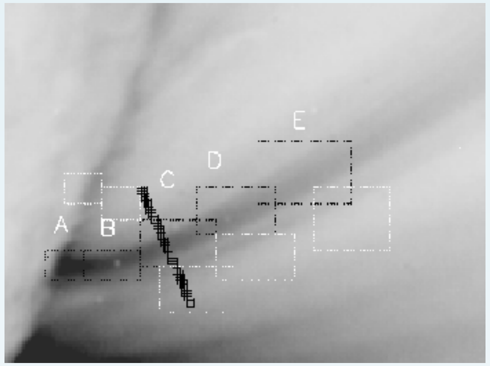
Re-introduced the EM loci method (Strong 1978) to AR loops. Isothermal !

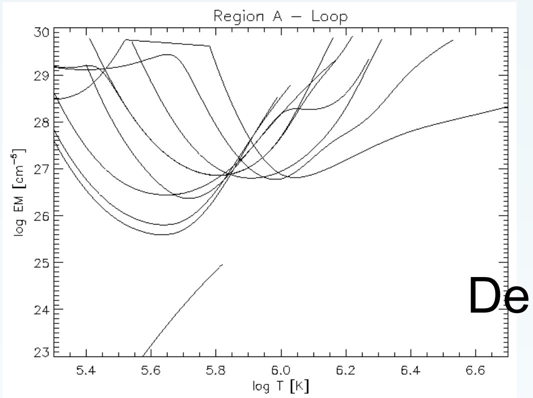
$$\frac{Iobs}{Ab(Y)\ Gji(Te)}$$

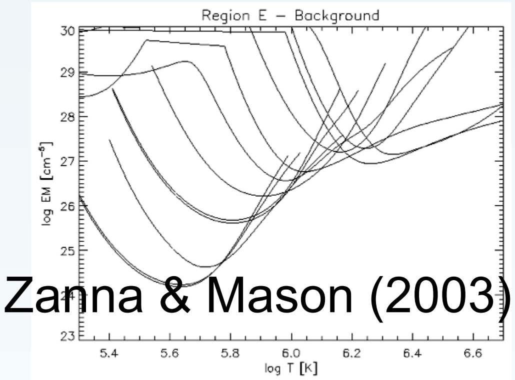




Del Zanna (2003)



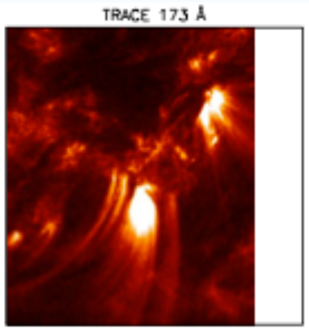


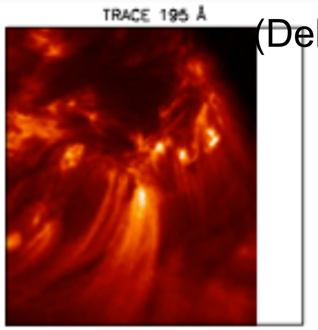


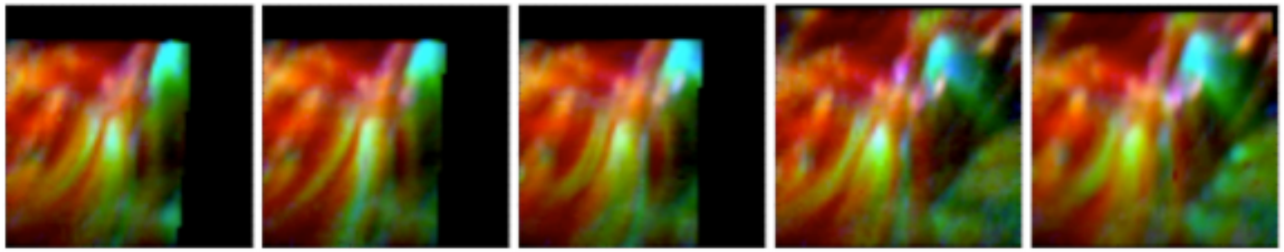
Del Zanna & Mason (2003)

SOHO CDS Ne VII (blue - 0.7 MK) Ca X   (green – 1 MK) Si XII (red – 2 MK)

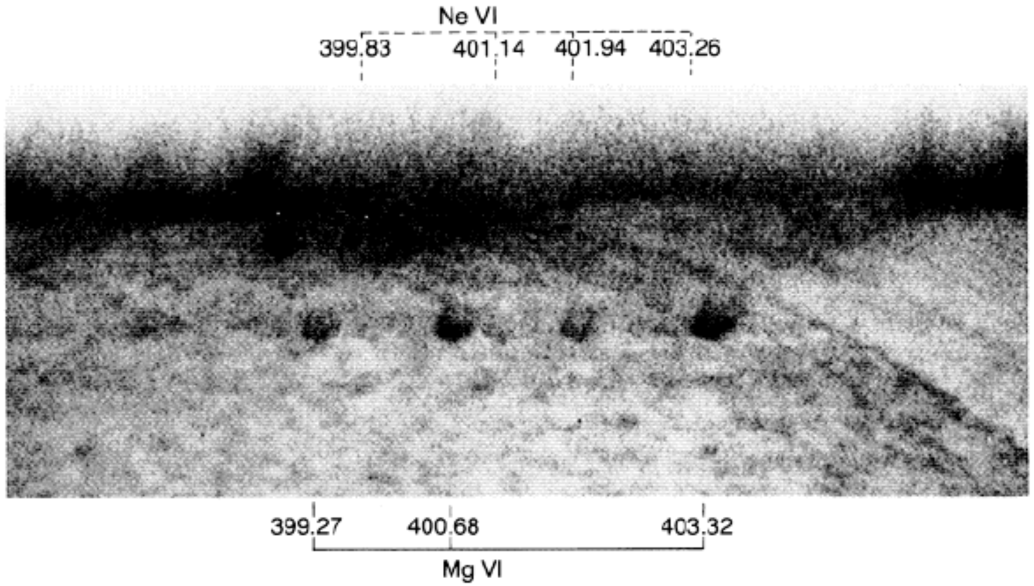
(Del Zanna et al. 2006)

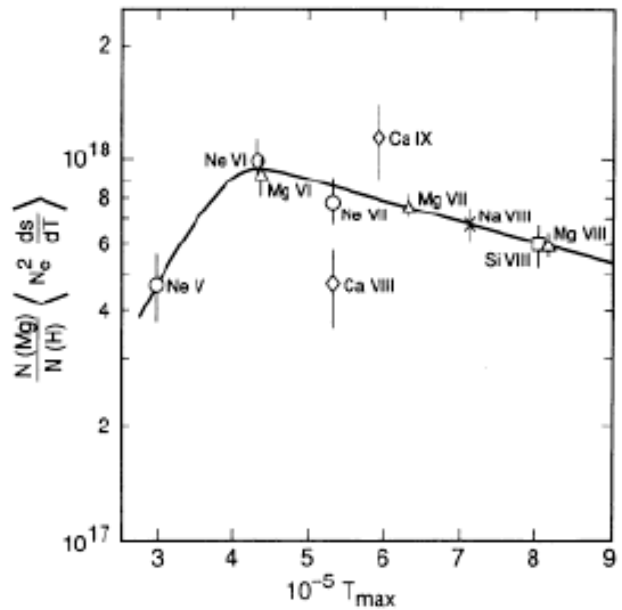






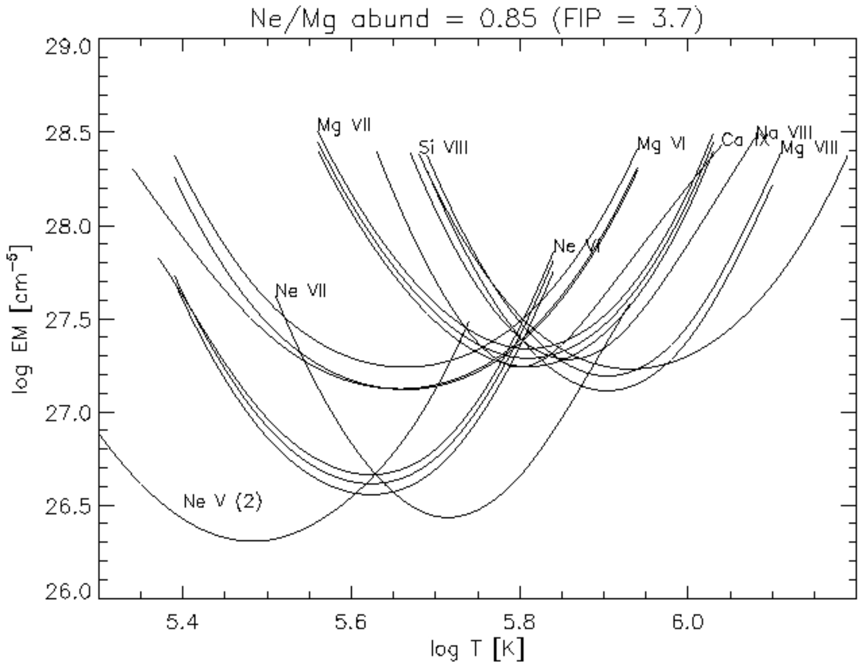
FIP effect overestimated in AR loops !





The Widing & Feldman (1993) diagnostic method assumes that the DEM has a continuous distribution, and gives high FIP (14).

However, the EM Loci curves are consistent with an FIP bias of 3.7, 4 times lower ! (Del Zanna 2003)



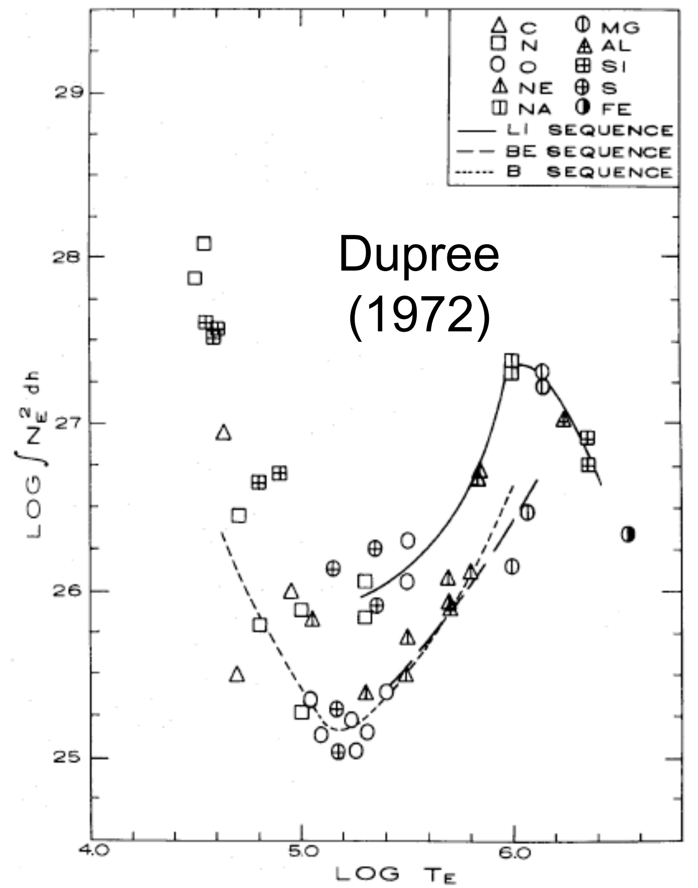
The problem of the ‘anomalous’ ions

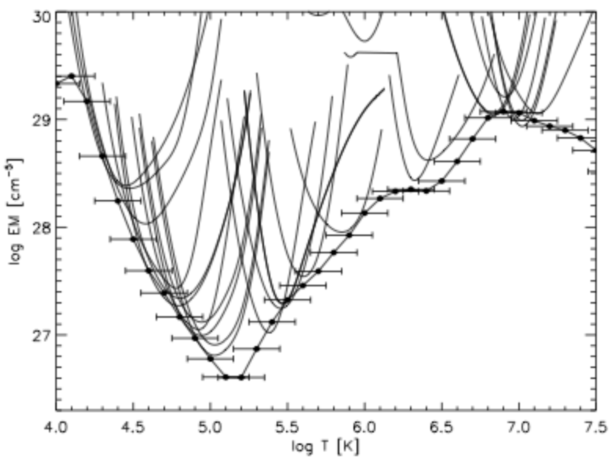
Anomalous EM for lines of the Li and Na isoelectronic sequences (from Burton et al. 1971).

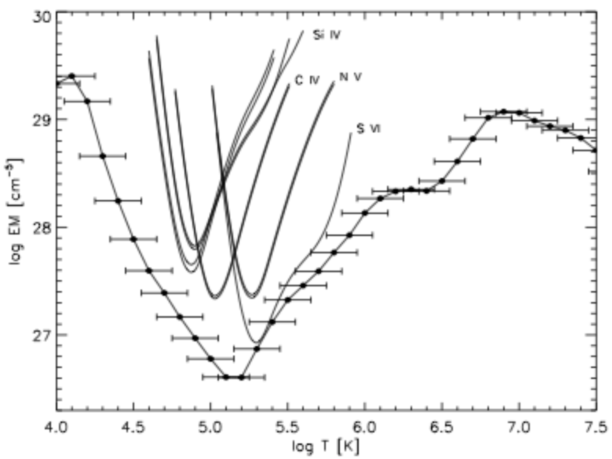
See Del Zanna (1999) and Del Zanna et al. (2001,2002)

Li-like N V and C IV are underestimated by factors of 3 and 10, while those of Ne VIII and Mg X are overestimated by factors of 5 and 10,respectively.

The problem is common to stellar coronae (Del Zanna et al. 2002).





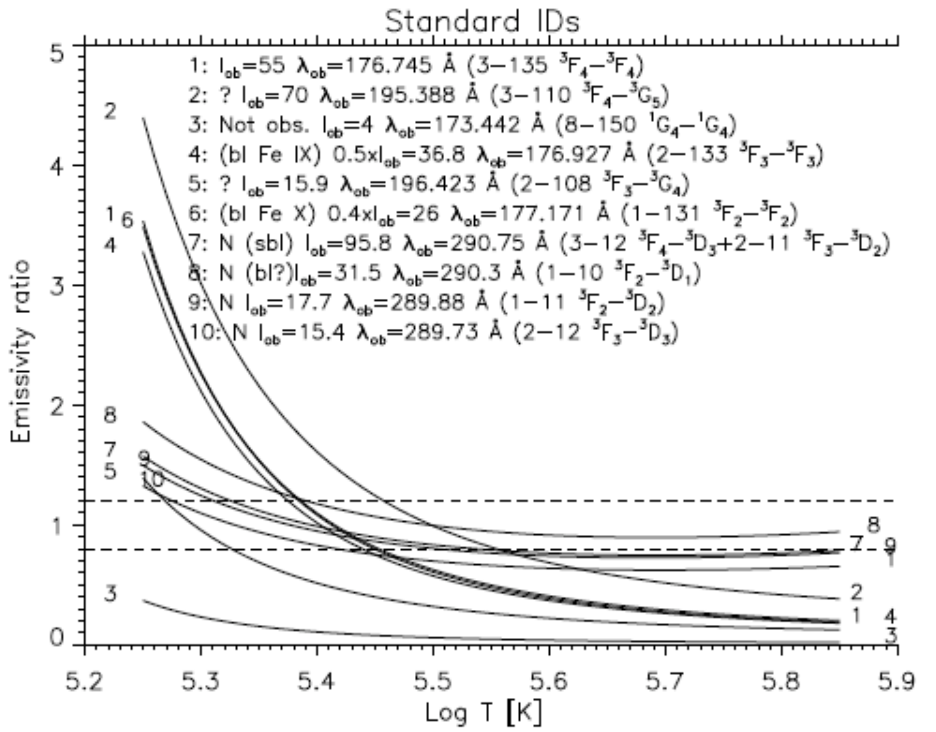


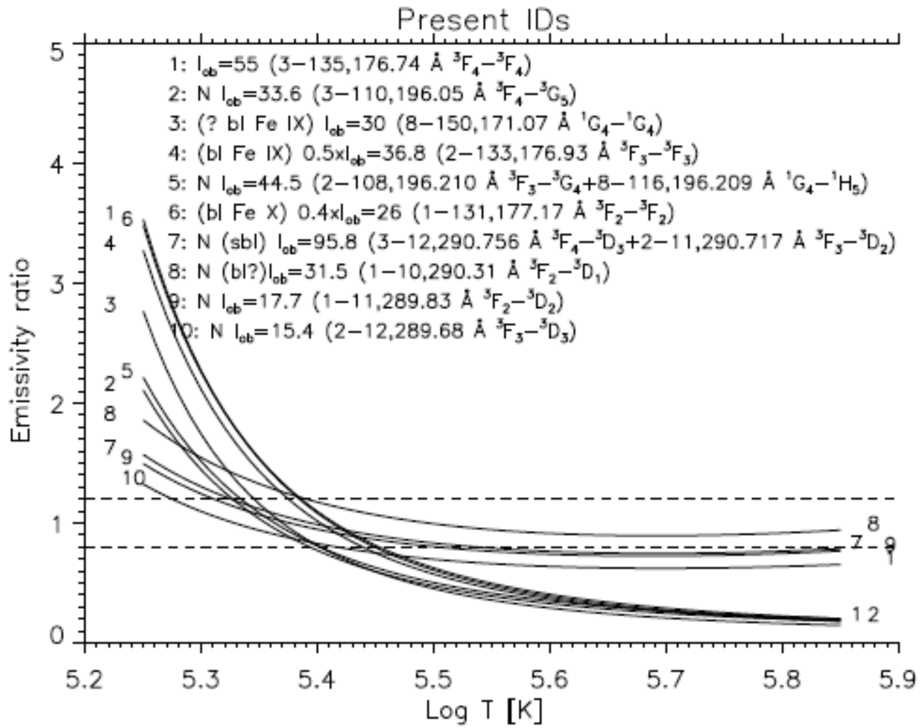
Fe VII – Te diagnostics

Del Zanna (2009): benchmarked Witthoeft & Badnell (2008) against laboratory (Fawcett's plates) and solar (Hinode EIS) data.

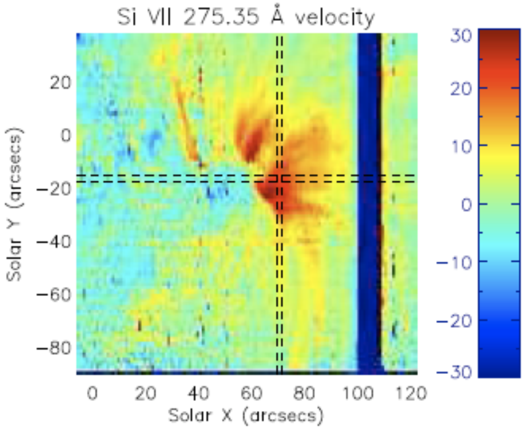
After two years: Many identifications from Ekberg are wrong (!?). Good agreement with new identifications.

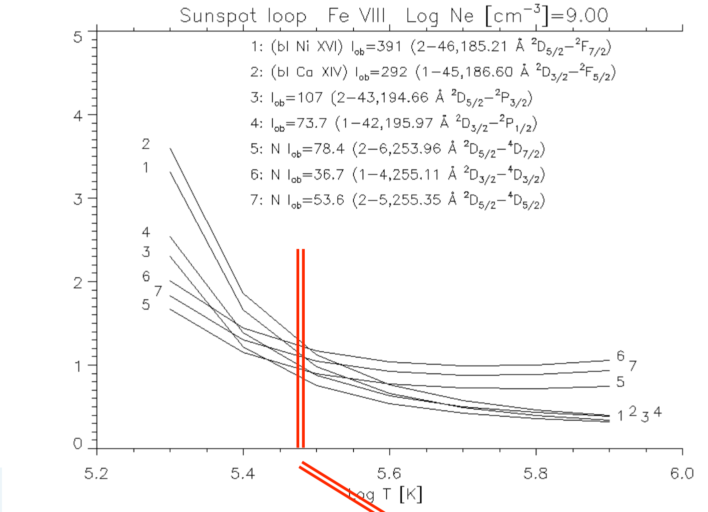
Also identified the decays of the 3d 4s ^3D_j (lines n.7,8, 9,10) and $^1D_2$: Te diagnostics.

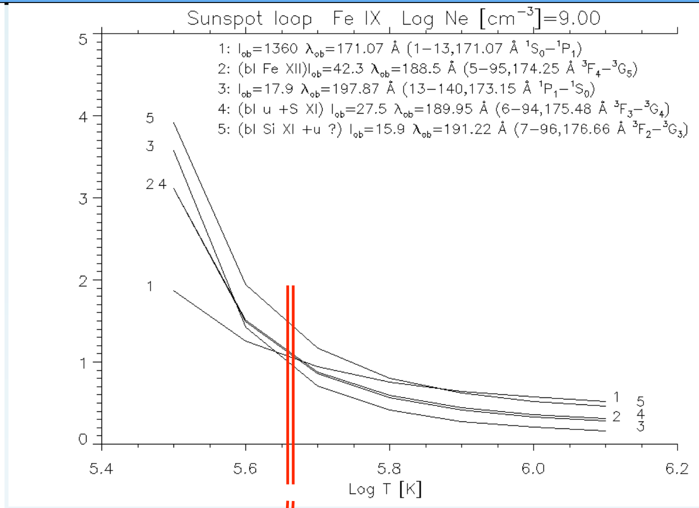




Te out of eq. for sunspot loops

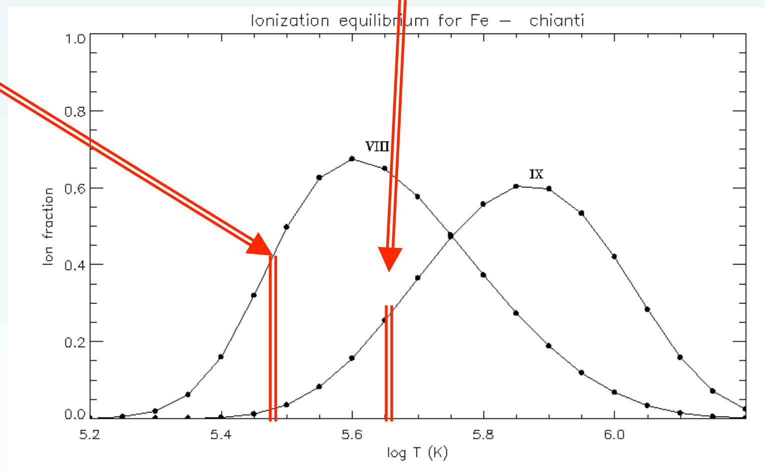






Del Zanna (2009a,b):
Te lower than To (ioniz. Eq.).

First (?) direct measurements after Skylab.

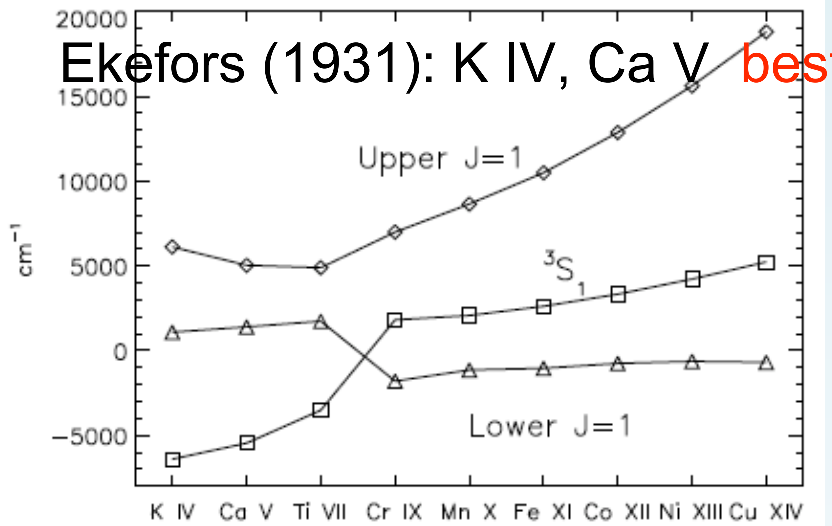


CHIANTI v.6 ioniz. Eq.

Fe XI – 6 years !

i	Conf.	Lev.	E_{exp}	E_{NIST}
1	$3s^2\,3p^4$	$^3P^e_2$	0	0
2	$3s^2\,3p^4$	$^3P^e_1$	12667	12667 (0)
3	$3s^2\,3p^4$	$^3P^e_0$	14306	14312 (-6)
4	$3s^2\,3p^4$	$^1D^e_2$	37743	37743 (-1)
5	$3s^2\,3p^4$	$^1S^e_0$	80831	80814 (16)
6	$3s\,3p^5$	$^3P^o_2$	283551	283558 (-7)
7	$3s\,3p^5$	$^3P^o_1$	293158	293158 (0)
8	$3s\,3p^5$	$^3P^o_0$	299163	299163 (0)
9	$3s\,3p^5$	$^1P^o_1$	361846	361842 (4)
10	$3s^2\,3p^3\,3d$	$^5D^o_0$	387544	-
11	$3s^2\,3p^3\,3d$	$^5D^o_1$	387726	-
12	$3s^2\,3p^3\,3d$	$^5D^o_2$	387940	-
13	$3s^2\,3p^3\,3d$	$^5D^o_3$	388268	-
14	$3s^2\,3p^3\,3d$	$^5D^o_4$	389227	-
15	$3s^2\,3p^3\,3d$	$^3D^o_2$	412856	-
16	$3s^2\,3p^3\,3d$	$^3D^o_3$	415426	-
17	$3s^2\,3p^3\,3d$	$^3D^o_1$	417049	-
18	$3s^2\,3p^3\,3d$	$^3F^o_2$	422844	-
19	$3s^2\,3p^3\,3d$	$^1S^o_0$	-	-
20	$3s^2\,3p^3\,3d$	$^3F^o_3$	426022	-
21	$3s^2\,3p^3\,3d$	$^3F^o_4$	430522	-
22	$3s^2\,3p^3\,3d$	$^3G^o_3$	-	-
23	$3s^2\,3p^3\,3d$	$^3G^o_4$	450211	-
24	$3s^2\,3p^3\,3d$	$^3G^o_5$	452416	-
25	$3s^2\,3p^3\,3d$	$^1G^o_4$	459218	-
26	$3s^2\,3p^3\,3d$	$^1D^o_2$	-	-
27	$3s^2\,3p^3\,3d$	$^3D^o_1$	-	-
28	$3s^2\,3p^3\,3d$	$^3P^o_0$	-	-
29	$3s^2\,3p^3\,3d$	$^3P^o_1$	484830	-
30	$3s^2\,3p^3\,3d$	$^3F^o_3$	485039	-
31	$3s^2\,3p^3\,3d$	$^3F^o_2$	-	-
32	$3s^2\,3p^3\,3d$	$^3F^o_4$	486413	-
33	$3s^2\,3p^3\,3d$	$^3D^o_2$	489378	-
34	$3s^2\,3p^3\,3d$	$^3P^o_2$	494013	496090 (-2077)
35	$3s^2\,3p^3\,3d$	$^3D^o_3$	497235	-
36	$3s^2\,3p^3\,3d$	$^1F^o_3$	525260	-
37	$3s^2\,3p^3\,3d$	$^3P^{o\dagger}_1$	531070	526480 (4590)
38	$3s^2\,3p^3\,3d$	$^3P^o_2$	531304	531290 (14)
39	$3s^2\,3p^3\,3d$	$^3S^{o\dagger}_1$	533445	533450 (-5)
40	$3s^2\,3p^3\,3d$	$^3P^o_0$	541777	541720 (57)
41	$3s^2\,3p^3\,3d$	$^3P^{o\dagger}_1$	541424	541390 (34)
42	$3s^2\,3p^3\,3d$	$^3D^o_3$	554321	554300 (21)
43	$3s^2\,3p^3\,3d$	$^3D^o_2$	561615	561610 (5)
44	$3s^2\,3p^3\,3d$	$^3D^o_1$	566396	566380 (16)
45	$3s^2\,3p^3\,3d$	$^1D^o_2$	578890	578860 (30)
46	$3s^2\,3p^3\,3d$	$^1F^o_3$	594047	594030 (17)
47	$3s^2\,3p^3\,3d$	$^1P^o_1$	623101	623080 (21)
48	$3p^6$	$^1S^e_0$	-	-

Ekefors (1931): K IV, Ca V best paper !



Atomic Data from the IRON Project

LXVIII. Electron impact excitation of Fe XI★

G. Del Zanna[1], P.J. Storey[2], and H.E. Mason[1]

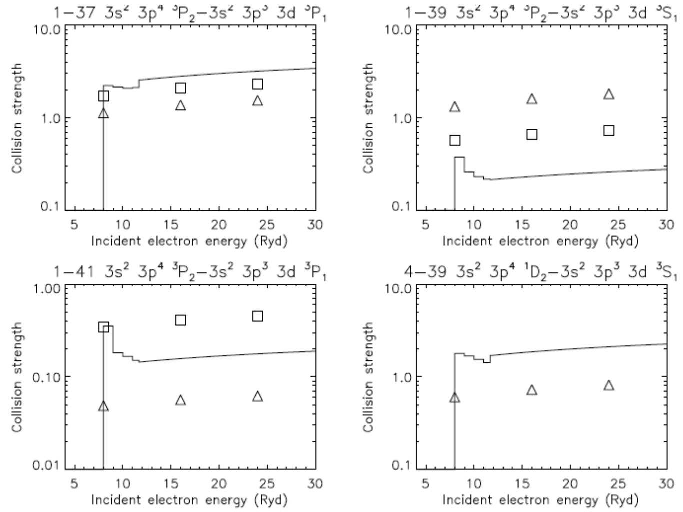


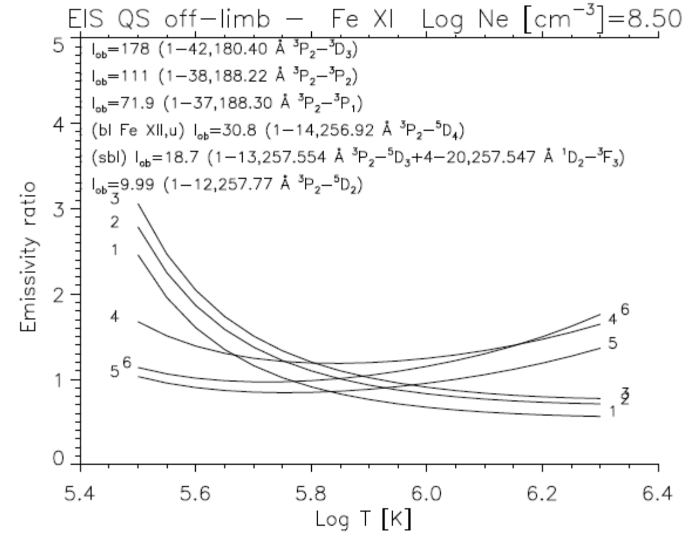
Fig. 7. Collision strengths for transitions involving the three $J = 1$ levels, averaged over 1 Ryd. Boxes indicate the GT99 values, while triangles the AK03 ones.

Table 3. Summary of line identifications for Fe XI.

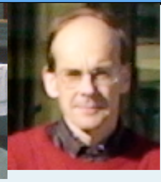
Del Zanna (2010)

i-j	λ_{exp} (Å)	λ_{obs} (Å)	ID	Diff. ID
6-103	168.929	? 168.929(10) Be76	N	
1-43	178.058	178.056(4) Be76	G66	
4-46	179.758	179.758(10) Be76	G66	
1-42	180.401	180.401(2) Be76 (bl)	G66	
2-44	180.594	180.595(4) Be76	F71	
3-44	181.130	181.131(10) Be76	G66	
2-43	182.167	182.167(2) Be76	G66	
4-45	184.793	184.793(10) Be76 (bl u)	FG66	
1-38	188.216	188.216(2) Be76	B77	F71 (188.299)
1-37	188.299	188.299(2) Be76	J93	B77(189.94)
2-41	189.123	189.123(4) Be76 (bl u)	B77	J93 (192.619)
3-41	189.711	189.723(5) N (bl)	B77	
1-36	190.382	190.382(5) N (bl u)	N	Be76 (S XI)
2-39	192.021	192.021(5) N (bl)	B77	
3-39	192.627	192.624(5) N (bl u)	B77	
2-38	192.813	192.811(5) N (bl O V, u)	F71	
3-37	193.512	- (bl Fe XII 193.509(2))		
4-41	198.538	198.555(10) Be76 (bl S VIII)	B77	Be76, J93
1-35	201.112	201.112(5) N (bl Fe XIII)	N	
4-39	201.734	201.734(10) Be76 (bl Fe XII)	B77	
1-34	202.424	202.424(10) Be76 (bl u)	N	B77 (201.575)
4-38	202.609	- (bl S VIII 202.608(10))		
4-37	202.705	202.710(10) Be76 (bl)		
1-30	206.169	206.169(10) Be76 (bl u)	N	
1-29	206.258	206.258(5) N	N	
2-34	207.751	207.749(5) N (bl u)	N	
2-33	209.771	209.771(5) N (bl u)		
1-20	234.730	234.73(2) D78	N	D78 (Fe XV)
1-18	236.494	236.494(10) Be76	N	
1-17	239.780	? 239.78(2) D78	N	
1-16	240.717	240.713(4) Be76 (bl Fe XIII)	N	
1-15	242.215	242.215(10) (bl) Be76	N	
4-21	254.596	254.600(5) N	N	
1-14	256.919	256.925(5) N (bl Fe XII)	N	
4-20	257.547	257.547(10) Be76 (sbl)	N	
1-13	257.554	257.547(10) Be76 (sbl)	J93	T98 (257.26 T)
1-12	257.772	257.772(4) Be76	J93	T98 (257.55 T)
1-11	257.914	257.914(5) N	N	T98 (257.78 T)
4-16	264.772	bl Fe XIV 264.787	N	
4-15	266.586	? 266.613(5) N (bl)	N	
21-79	266.759	266.755(5) N (bl u)	N	
4-9	308.544	308.544(4) (sbl) Be76	F71	
16-67	308.991	308.991(4) B00	N	
14-54	326.323	326.323(4) B00	N	
1-7	341.113	341.112(10) Be76	F71	
2-8	349.046	349.046(8) S76 (bl Mg VI)	F71	
1-6	352.670	352.670(10) Be76	F71	
2-7	356.519	356.519(8) S76 bl	F71	
3-7	358.613	358.621(8) S76 bl	F71	
2-6	369.163	369.161(10) Be76	F71	
4-6	406.822	406.791(4) TN94	N	
6-21	680.406	? bl 680.28(1) F97	N	
6-14	946.289	946.29(1) F97	N	
13-32	1018.90	1018.89(1) F97 (bl)	N	F97 (Ar XII)
14-32	1028.95	1028.95(1) F97 (bl)	N	
16-32	1408.71	1408.70(1) F97	N	
13-25	1409.44	1409.45(1) S77	N	
14-25	1428.76	1428.75(1) S77	N	
2-5	1467.07	1467.06(2) S77	J71	
14-24	1582.55	1582.56(2) S77	N	FD77,S77
14-23	1639.77	1639.78(3) S77 (bl O VII)	N	S77
1-4	2649.50	2648.71(2) S77 (air)	S77	
2-4	3988.00	3986.8(5) Je71 (air)		
21-24	4567.46	4566.2(5) Je71 (air)	MN77	
1-2	7894.03	7891.8(1) Je71 (air)		

New Te diagnostics



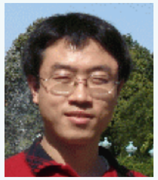
Good things come to those who wait…

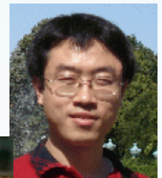
- Fe VII: Witthoeft et al. (2008) S
  Del Zanna (2010) ID
- Fe VIII: Griffin et al. (2000) S
  Del Zanna (2010) ID


- Fe IX: Storey et al. (2002) S
- Fe X: Del Zanna, Berrington, Mason (2004) S, ID
- Fe XI: Del Zanna, Storey, Mason & Del Zanna 2010 S, ID


- Fe XII: Storey et al. 2005 (S); Del Zanna & Mason (2005) S, ID
- Fe XIII: Storey & Zeippen (2010) S
- Fe XIV: Storey et al. (2000); Liang et al. (2010) S
- Fe XV Berrington et al. (2005)

- Fe XVII: Loch et al. (2006), Liang et al. (2010).
  ID: Del Zanna & Ishikawa (2009).
- Fe XVIII: Witthoeft et al.(2006). Del Zanna (2006).
- Fe XX: Witthoeft, Del Zanna, Badnell (2007)

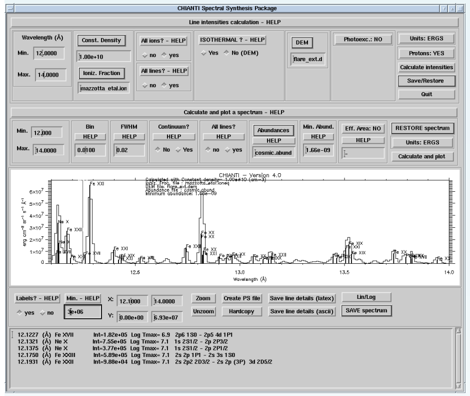



- Fe XXIII Chidichimo et al. (2005) S; Del Zanna et al. (2005) ID
- Fe XXIV Whiteford et al. (2002) S; Del Zanna (2006) ID
-

Atomic Data

- **APAP Network** http://www.apap-network.org/

- **CHIANTI database** (not funded by STFC)
  SolarSoft distribution, GUI programs, documentation, www pages.



- Basic atomic data and spectral line emissivities for plasma modelling were imported from CHIANTI into a MySQL database accessible via **AstroGrid: www2.astrogrid.org.** Unfortunately, AstroGrid is not funded by STFC.

- Del Zanna & Mason are part of the **Virtual Atomic and Molecular Data Centre (VAMDC)** www.vamdc.eu, an EU-funded international collaboration for the provision of atomic and molecular data.

Conclusions

Excellent agreement (within 10%) between theoretical and observed line intensities for stellar coronae.
A novel benchmark work has established a large number of new line identifications and spectral diagnostics.

We have made a great progress, but after 40 years, some problems are still with us.. A daunting amount of work is still needed (who ?)

Thank you Helen

CDS meeting 1998