Solar spectral analysis

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How to measure Te from XUV spectroscopy
(or how good R-matrix e scattering calculations are)

Science & Technology Facilities Council

UNIVERSITY OF CAMBRIDGE

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:

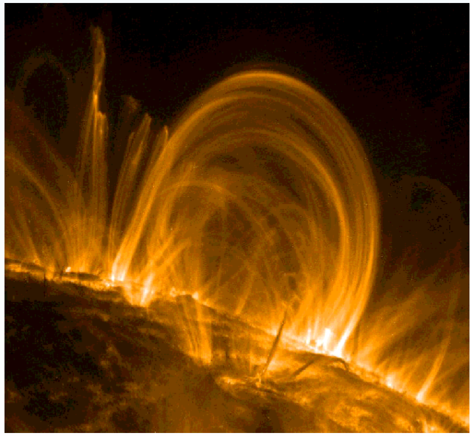
$$F_{ji}(N_e, T_e) = C \frac{I_{ob} N_e}{N_j(N_e, T_e)\, A_{ji}}$$

Maxwellian e,p, stationary, collisionally-excited, optically thin.

Result: a large number of revised wavelengths (with uncertainties), new identifications, level energies and new diagnostic lines to measure Ne, Te.

Typically, one ion in 2-5 years..

Will give examples on how to measure Te in solar corona.
We had SOHO SUMER, CDS spectroscopy.
Now we have Hinode/EIS for coronal diagnostics.



EM, DEM methods to obtain Te

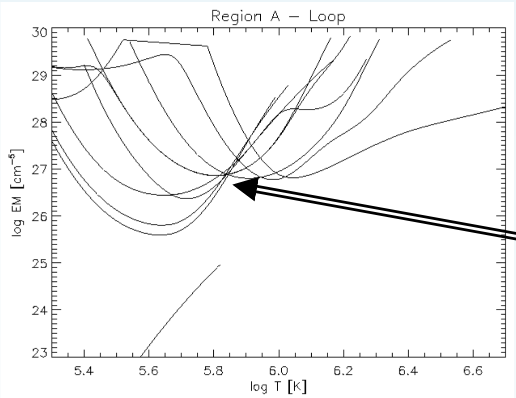
$$I_{ji} = \int f\ Ab(Y)\ G_{ji}(T_e)\ N_e^2\ dh \cong Ab(Y) \int G_{ji}(T_e) dT < \int N_e^2\ dh / dT >$$

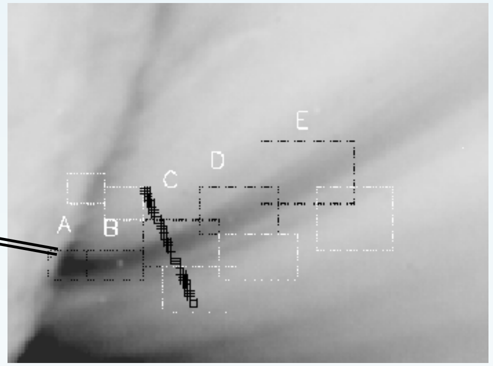
DEM (T)

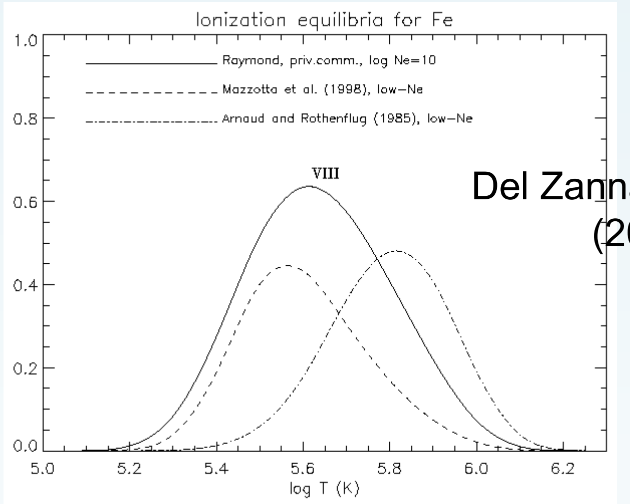
$$EM = \int N_e(h)^2\ dh$$

Depend on accuracy of excitation/ radiative data, mostly on ionization equilibrium.

EM Loci $\dfrac{Iobs}{Ab(Y)\ Gji(Te)}$



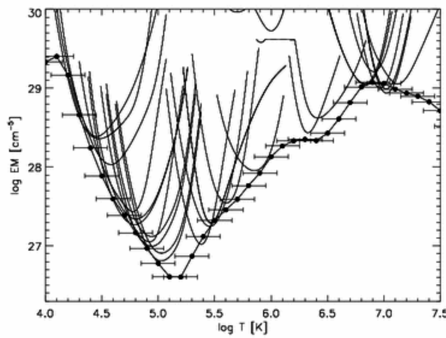




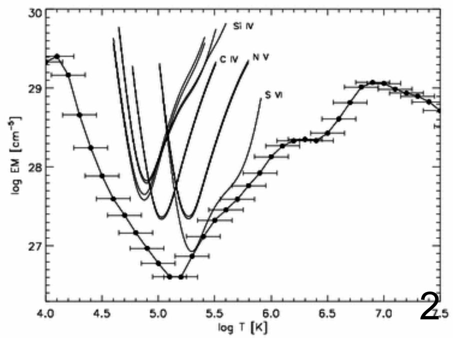
Del Zanna & Mason (2003)

However, large discrepancies are present (also in stars, as first shown in Del Zanna et al. 2002)

‘normal’ ions



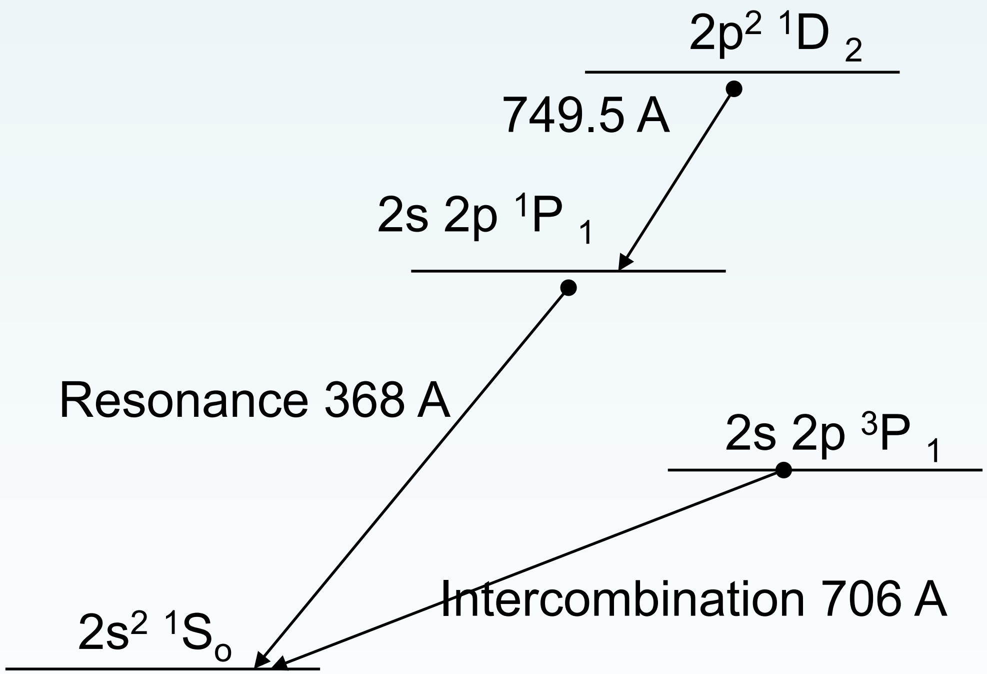
‘anomalous’ ions

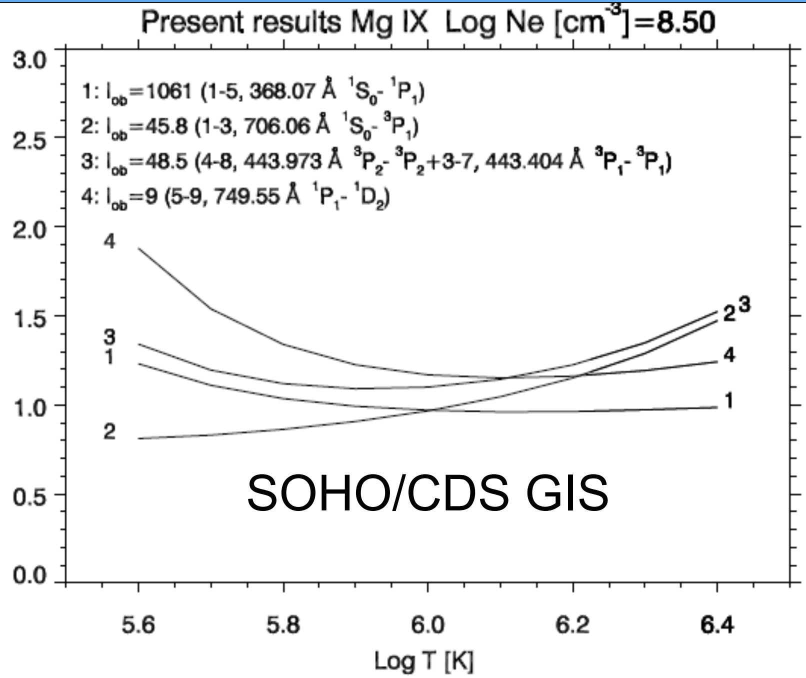


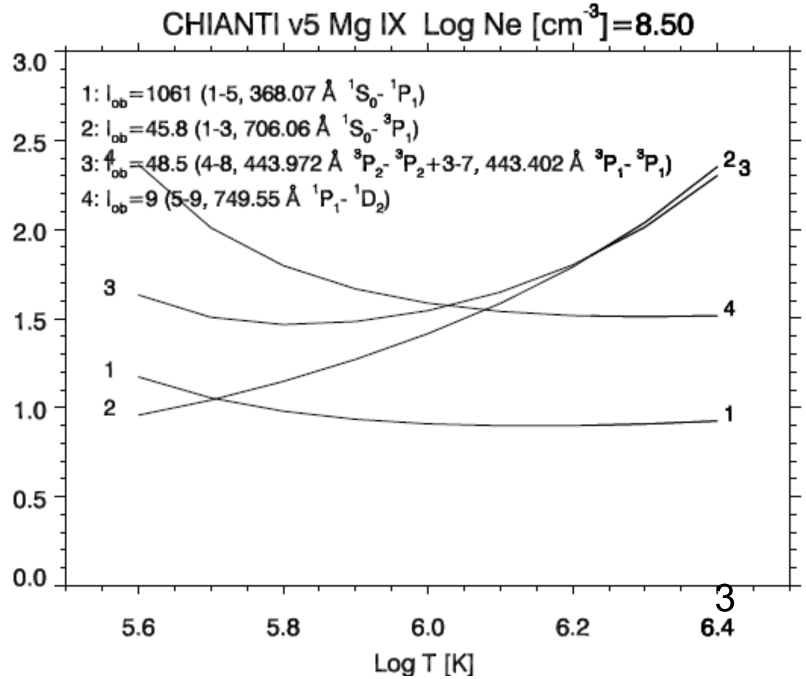
Direct measurement: Mg IX

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

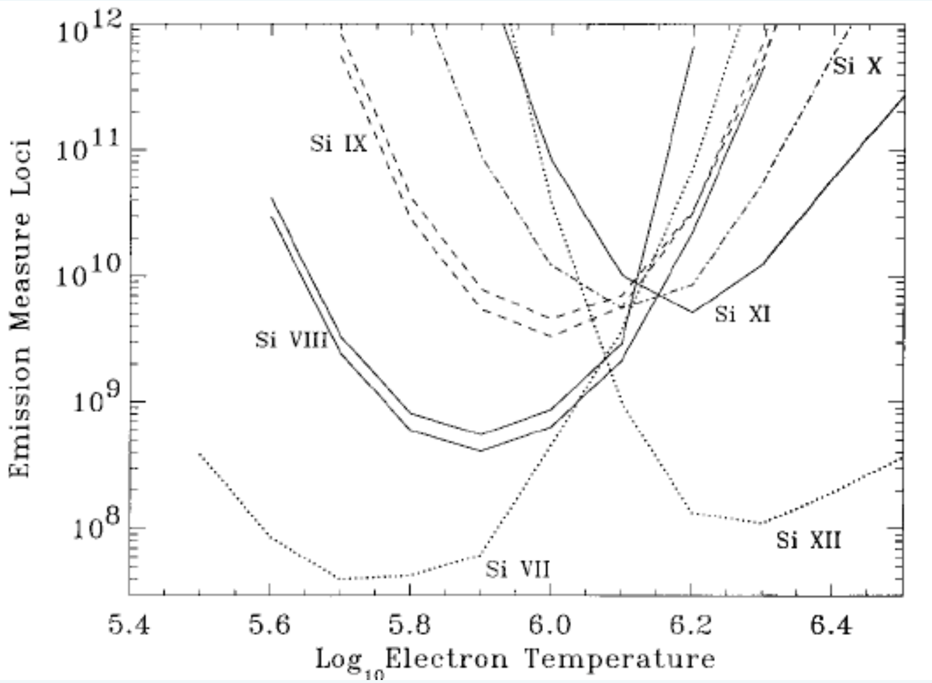
Best Te diagnostic for the 1 MK corona.
Te in CH underestimated by a factor of 2

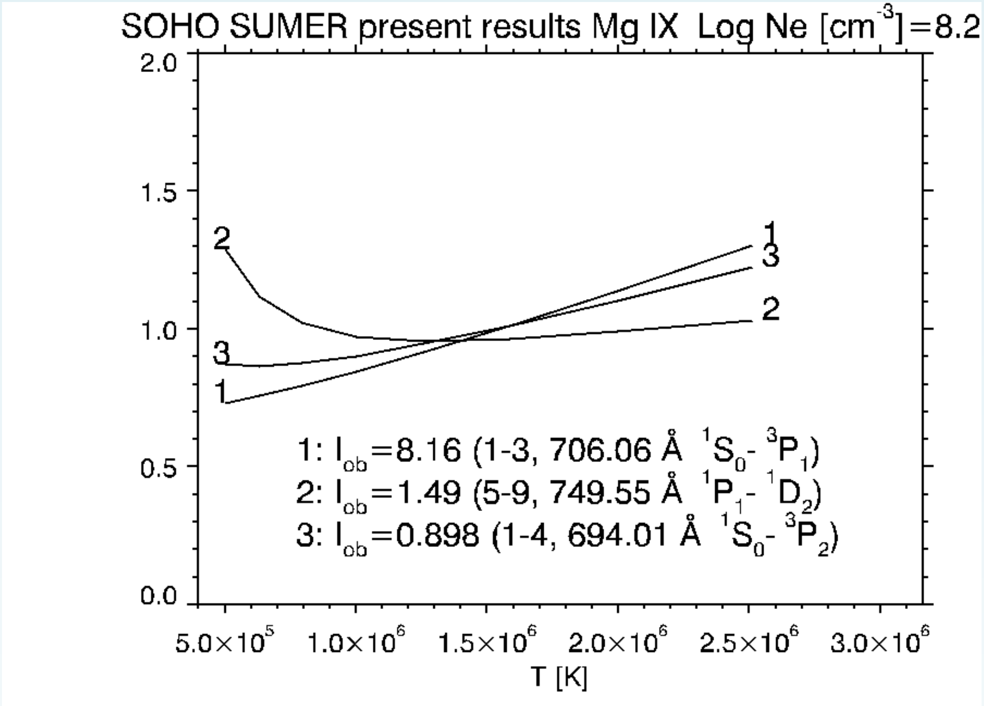






Mg IX: excellent agreement



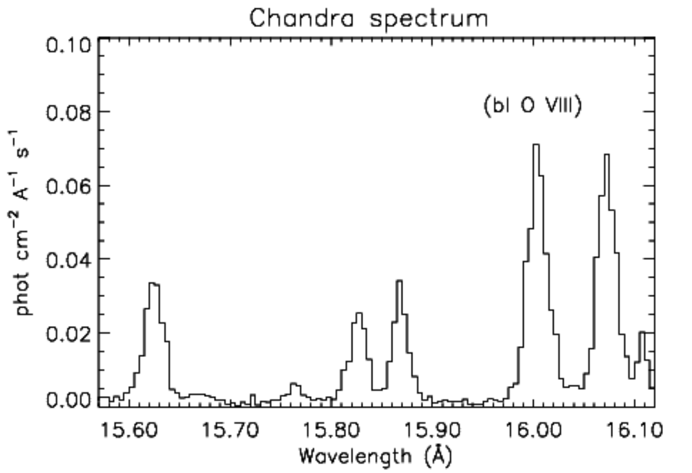


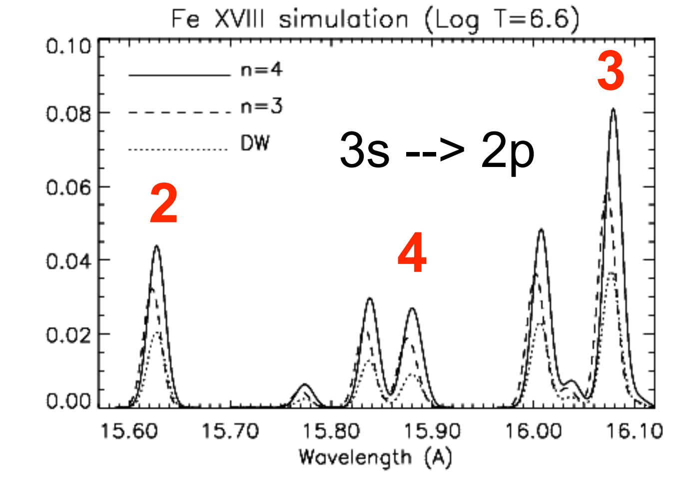
EM modeling: Isothermal plasma at

Te=1.35 MK (Feldman et al. 1999)
(SOHO/SUMER off-limb QS)

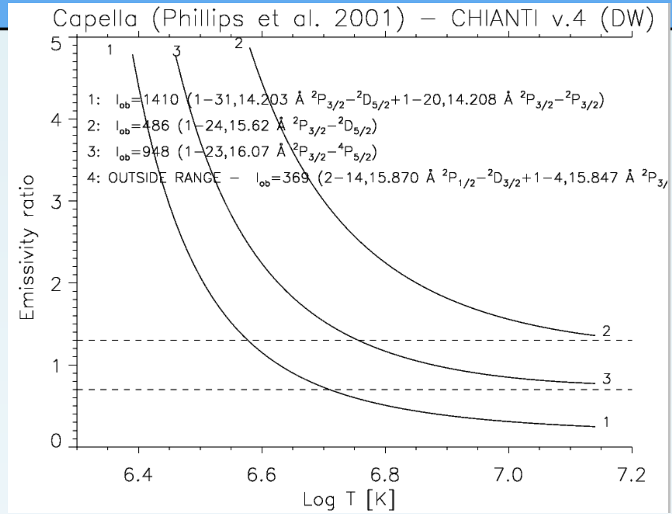
Direct line ratios from Mg IX
(Del Zanna Rozum Badnell 2008).

Fe XVIII

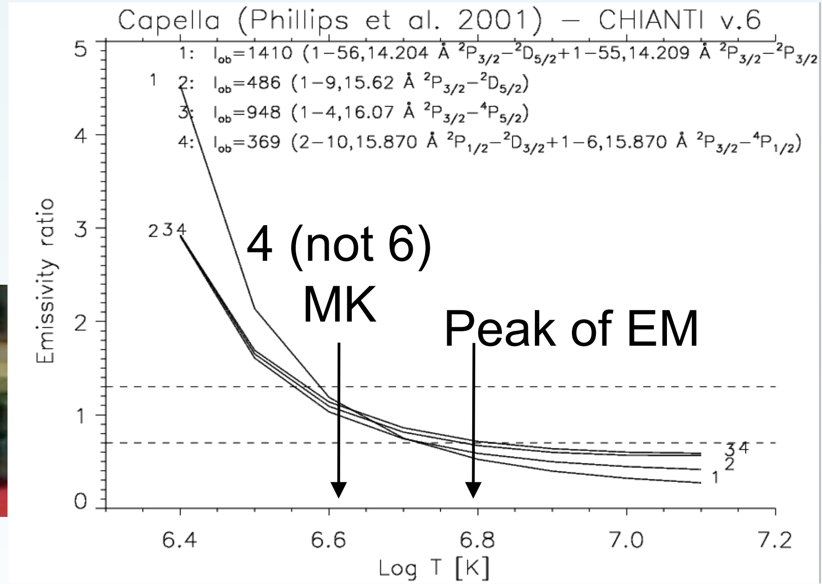


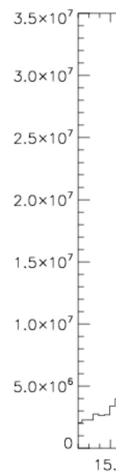


DW:



R-matrix:
Witthoeft et al. (2006)

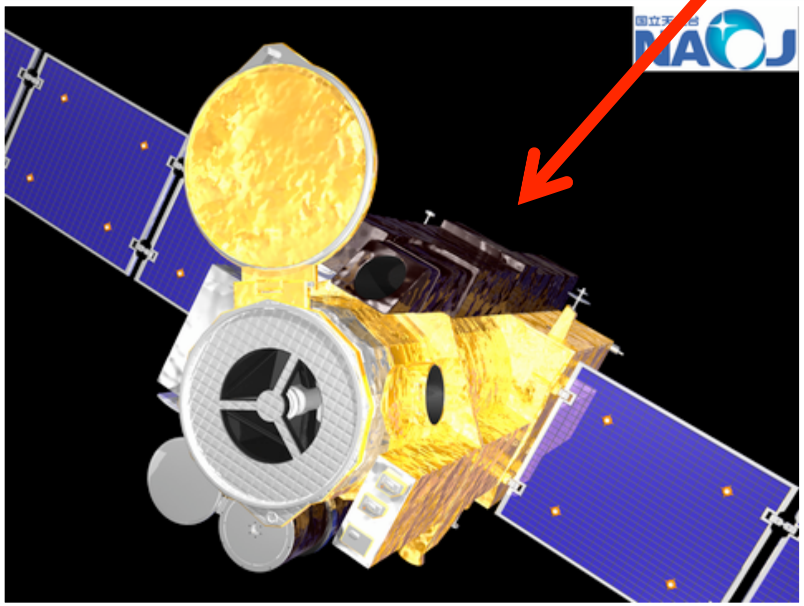


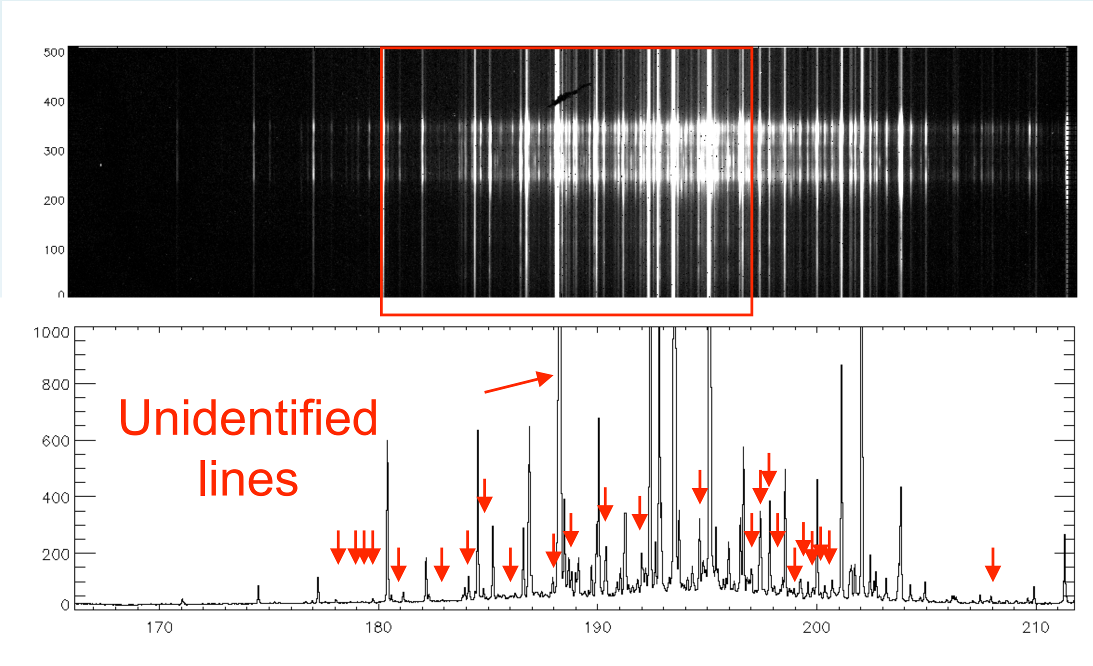


The large discrepancies for the strong 3s--> 2p transitions have been resolved.

New diagnostics to measure electron temperatures and densities (Del Zanna 2006). Same issues with Fe XVII.

Hinode EIS SW





166 – 212 A.
Almost as good as B.Fawcett's plates.

Benchmark structure – Fe XI

The 48 configurations used within SUPERSTRUCTURE. 4l,5l correlation orbitals

Even	Odd
c1: $3s^2\ 3p^4$	c2: $3s\ 3p^5$
c4: $3p^6$	
c5: $3s\ 3p^4\ 3d$	c3: $3s^2\ 3p^3\ 3d$
	c6: $3p^5\ 3d$
c9: $3s^2\ 3p^2\ 3d^2$	
c8: $3p^4\ 3d^2$	c7: $3s\ 3p^3\ 3d^2$
c11: $3s\ 3p^2\ 3d^3$	c10: $3s^2\ 3p\ 3d^3$
	c12: $3p^3\ 3d^3$

$3s^2\ 3p^3\ 4l$	$3s\ 3p^4\ 4l$	$3p^5\ 4l$	$3s^2\ 3p\ 3d\ 4l$	l=0,1,2,3
$3s^2\ 3p^3\ 5l$	$3s\ 3p^4\ 5l$	$3p^5\ 5l$	$3s^2\ 3p\ 3d\ 5l$	l=0,1,2,3

Bhatia, Doschek (1996); 4 conf. green

Fawcett (1986): 8 conf. green+blue

Aggarwal and Keenan (2003): green+ red

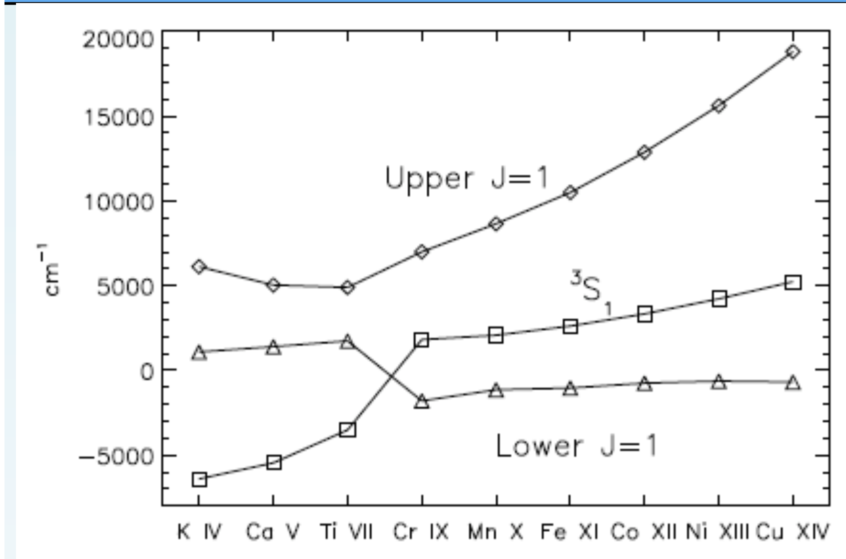
Atomic Data from the IRON Project

LXVIII. Electron impact excitation of Fe XI★

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

Fe XI (Iron Project)

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	$3s^2\ 3p^3\ 3d$	$^3P^o_1$ †	531070	526480 (4590)
38	$3s^2\ 3p^3\ 3d$	$^3P^o_2$	531304	531290 (14)
39	$3s^2\ 3p^3\ 3d$	$^3S^o_1$ †	533445	533450 (-5)
40	$3s^2\ 3p^3\ 3d$	$^3P^o_0$	541777	541720 (57)
41	$3s^2\ 3p^3\ 3d$	$^3P^o_1$ †	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	$3p^6$	$^1S^e_0$	[illegible]	[illegible]



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

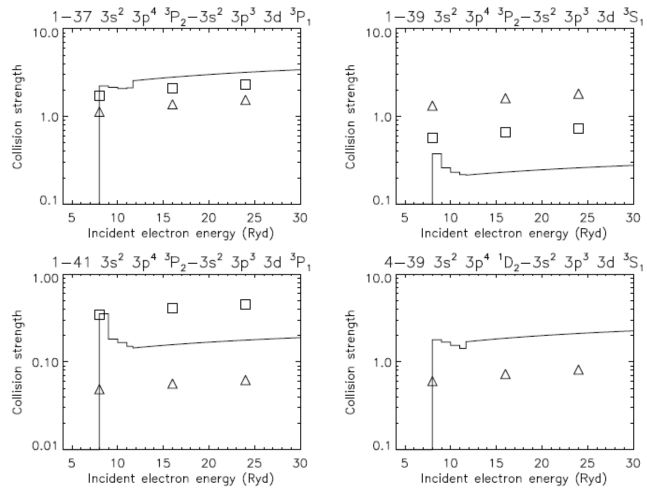


Fig. 7. Collision strengths for transitions involving the three $J = 1$ levels, averaged over 1 Ryd. Boxes indicate the GT99 values, while triangles the AK03 ones.

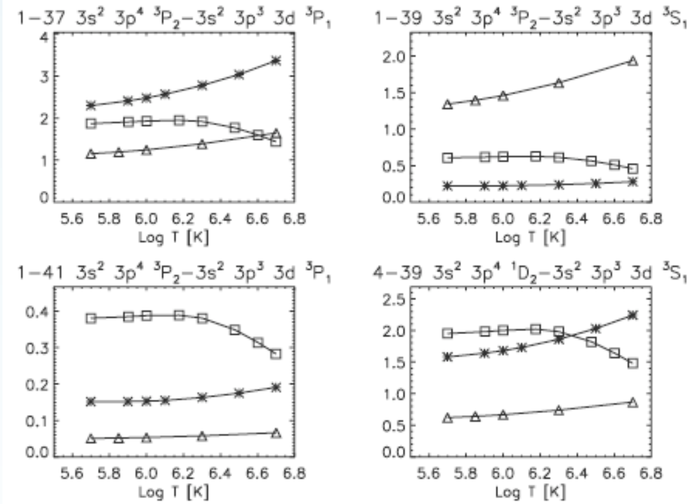
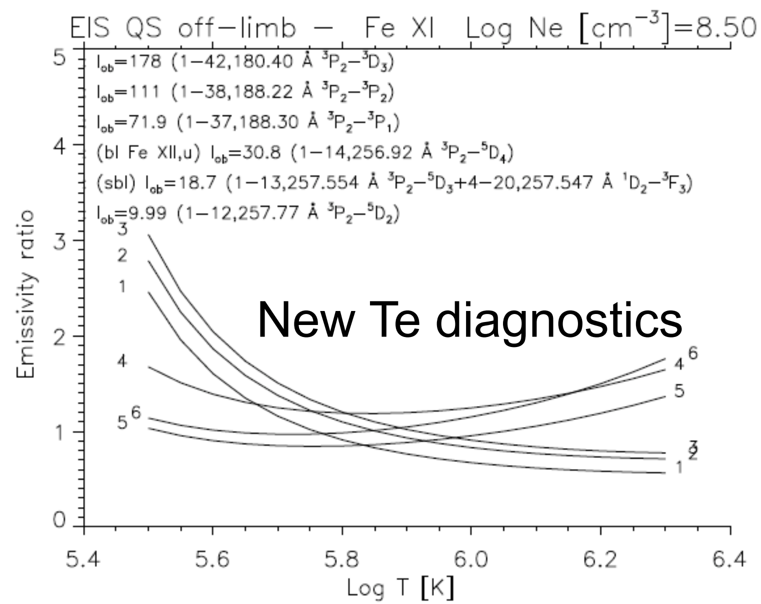


Table 3. Summary of line identifications for Fe XI.

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)		

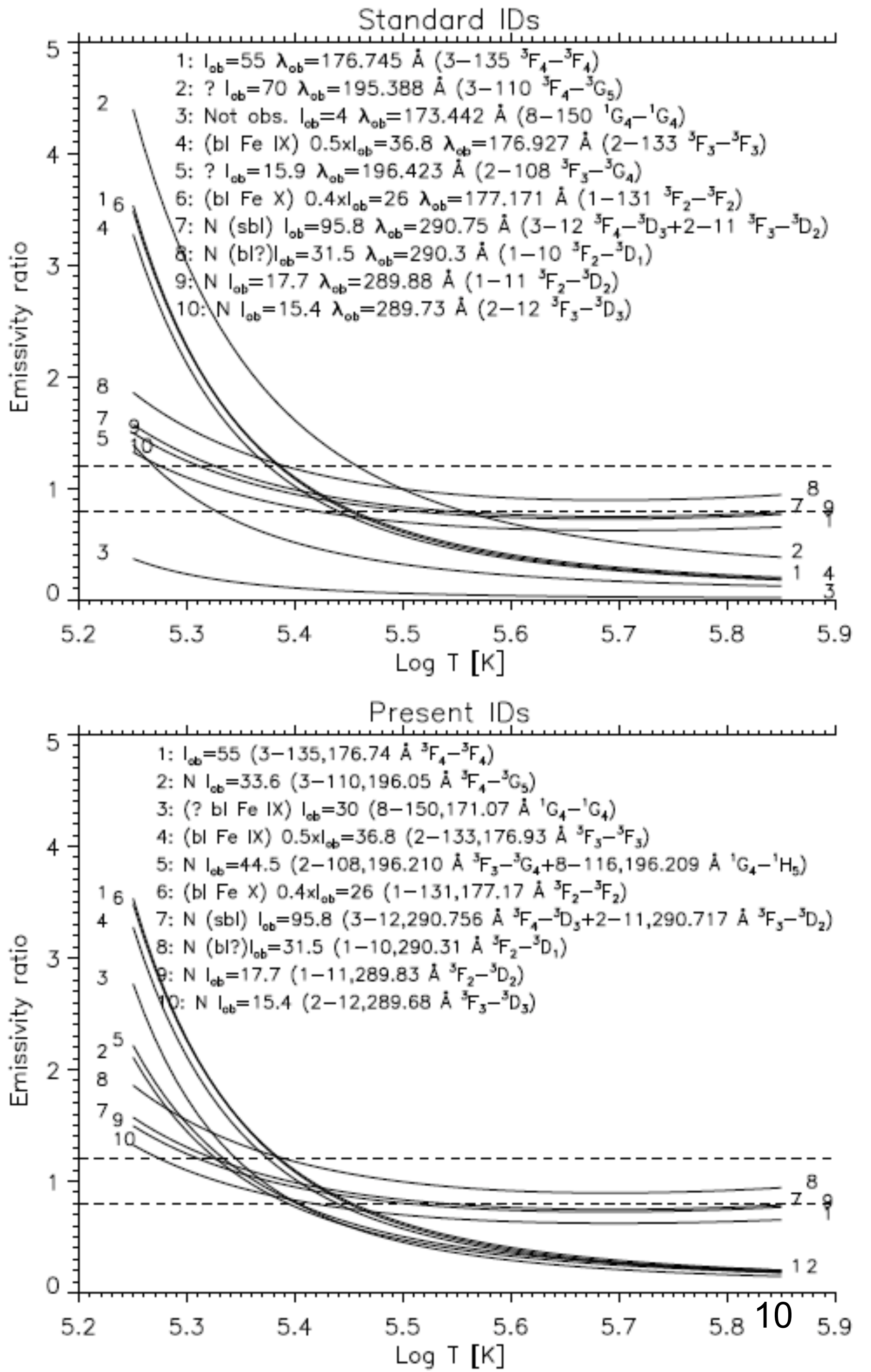


Fe VII – Te diagnostics

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.



Fe VIII – Te diagnostic

- Very complex target.

- IP R-matrix calculation gives good agreement when collision strengths are scaled (Del Zanna 2009).

- First identifications of the lowest levels of the 3s2 3p5 3d2. The decays from the ^{4}Dj are strong-ish lines in Hinode EUV spectra. The ratio with any of the other EUV lines is a temperature diagnostic (Del Zanna 2009).

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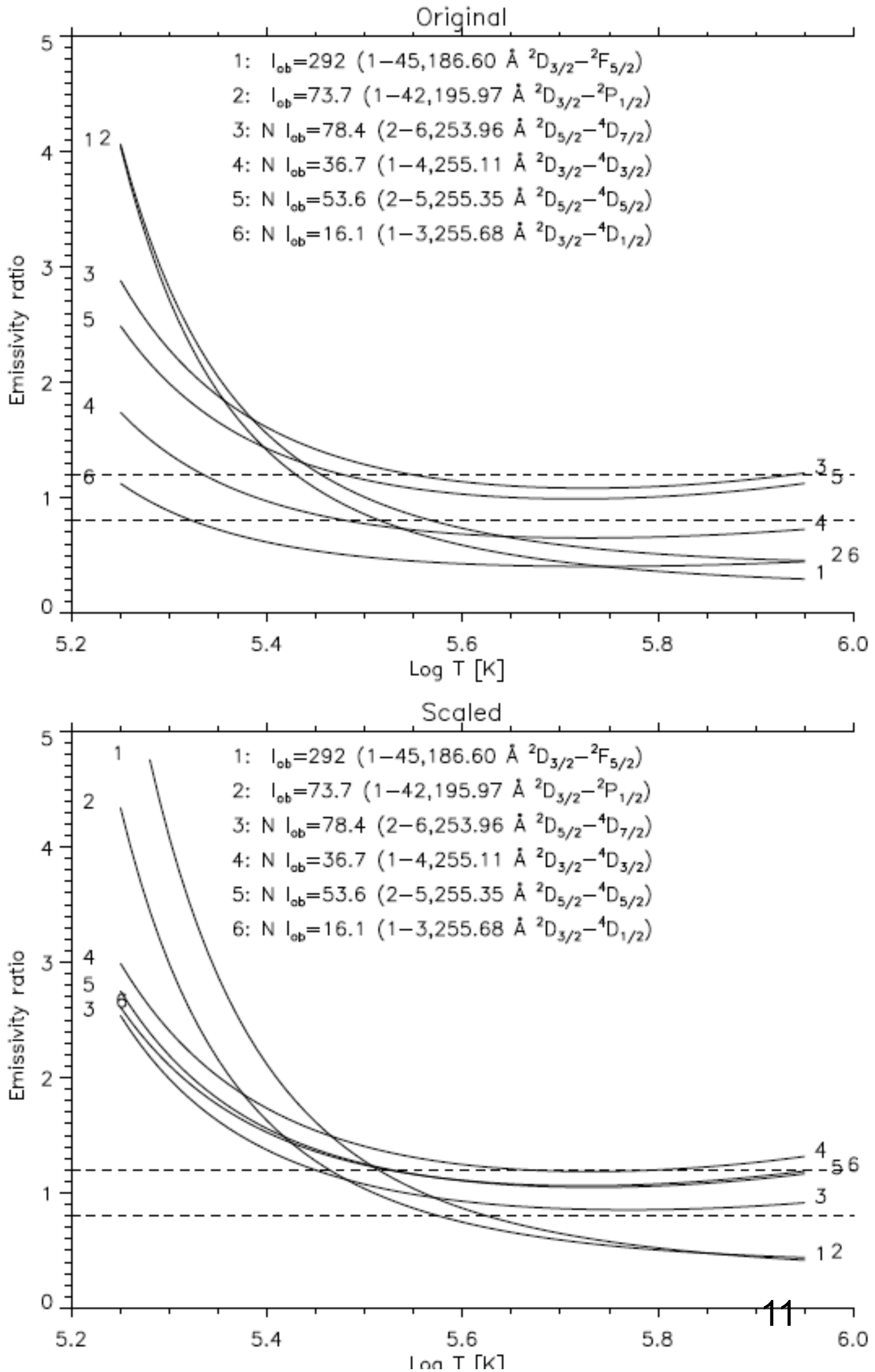
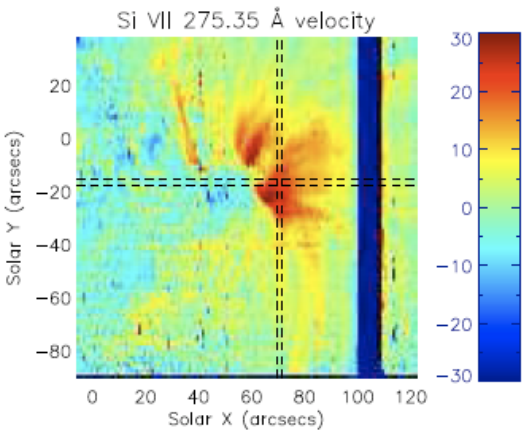
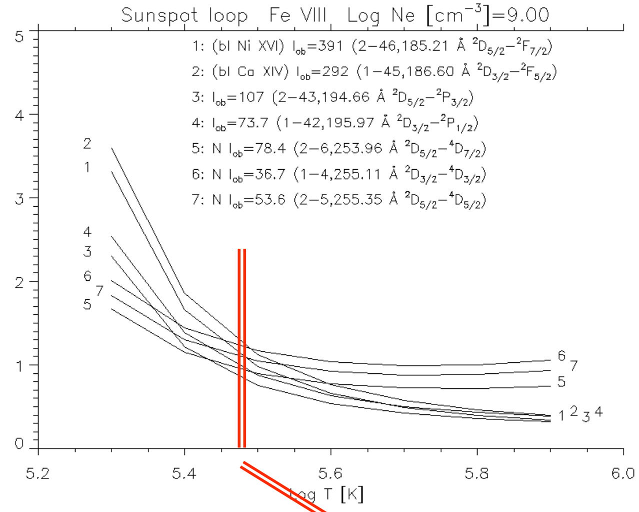
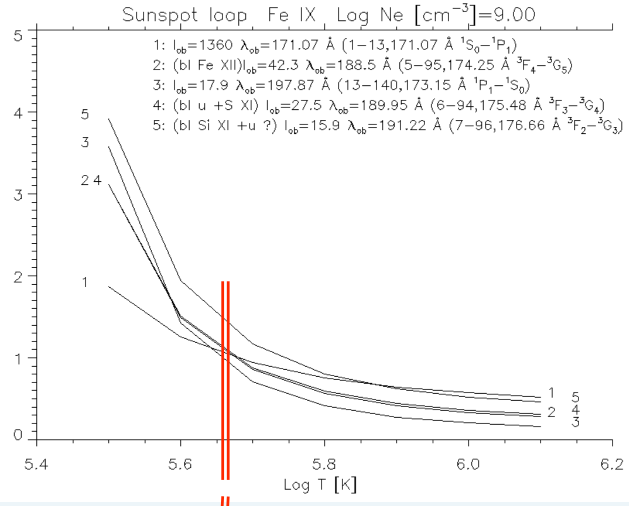


Te out of eq. for sunspot loops

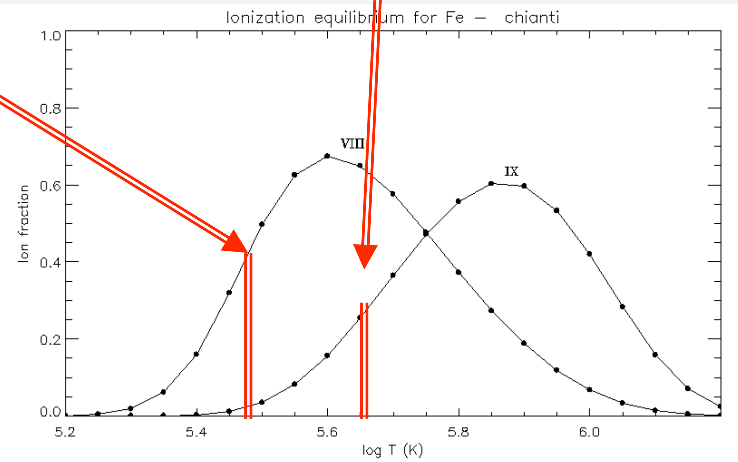






Del Zanna (2009a,b):
Te lower than To (ioniz. Eq.).

First (?) direct measurements after Skylab.

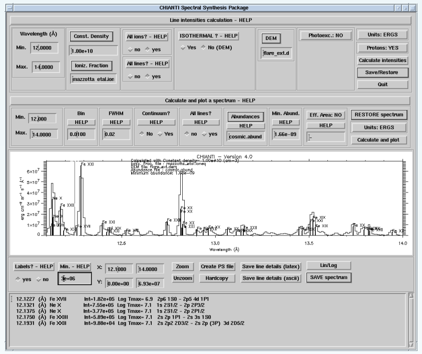


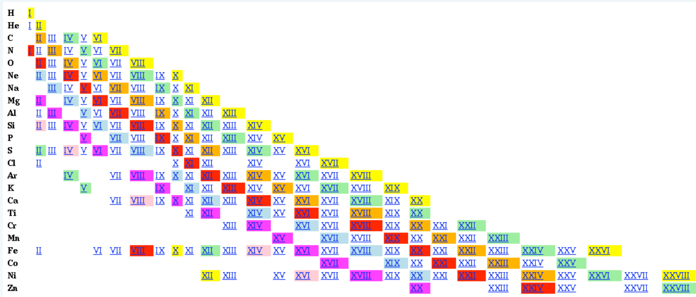
CHIANTI v.6 ioniz. Eq.

Atomic Data

- **APAP Network** http://www.apap-network.org/
- Scattering calculation -> **ADAS**

- **CHIANTI database** (not funded in UK)
  RAS award in 2010 !
  main database for XUV solar physics.
  New format to be introduced in 2011





- I imported basic atomic data and spectral line emissivities for plasma modelling from CHIANTI into a MySQL database accessible via **AstroGrid: www2.astrogrid.org.** (AstroGrid is not funded by STFC).

- Del Zanna & Mason: **Virtual Atomic and Molecular Data Centre (VAMDC)**
  www.vamdc.eu EU-funded 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.

Future: high-resolution EUV (Solar Orbiter, Solar-C) and X-ray solar spectroscopy -> need for ever more accurate atomic data!

Thank you