Spectroscopic plasma diagnostics for the XUV

From stars to atoms…

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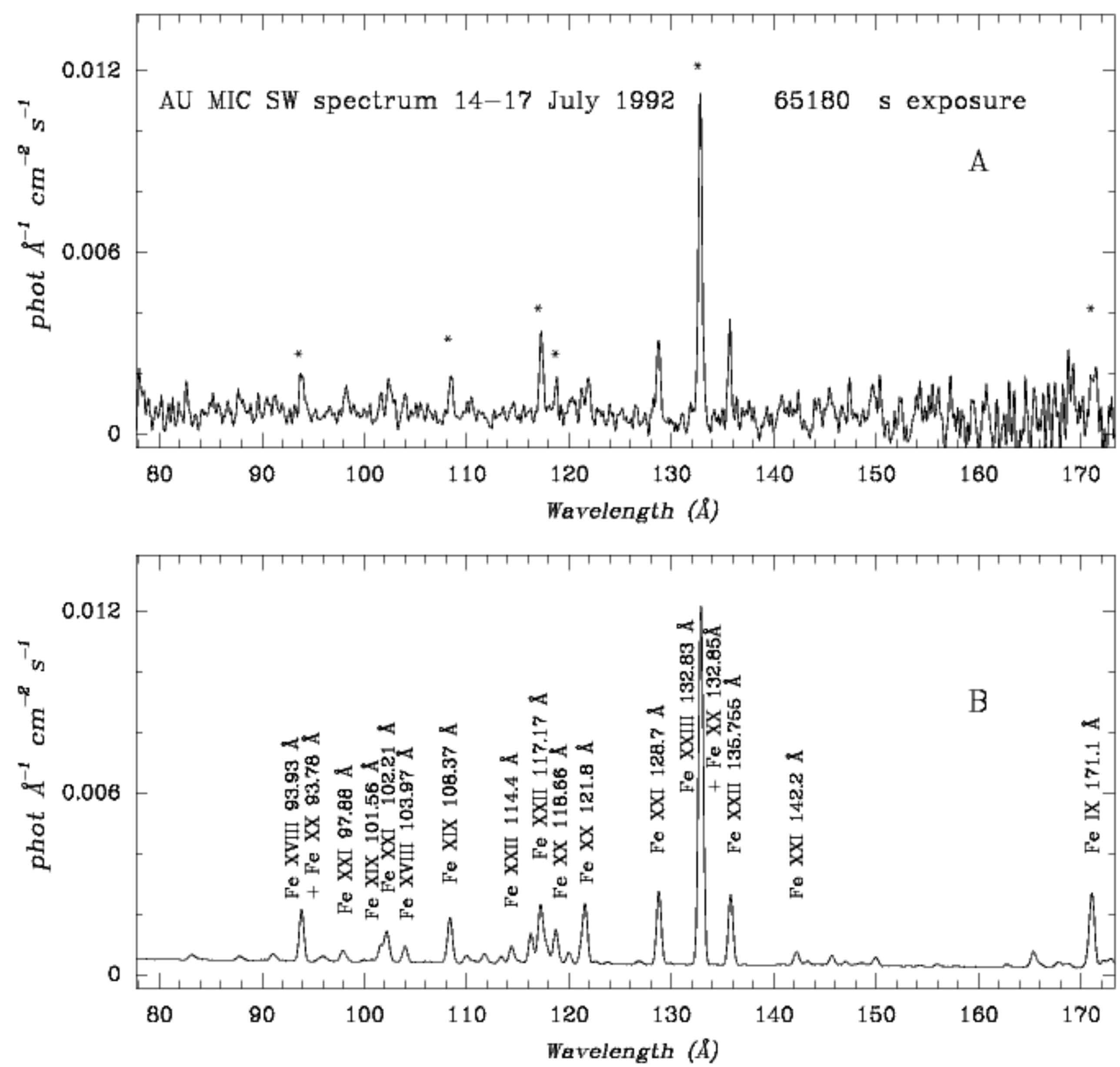
Science & Technology Facilities Council

VAMDC Virtual Atomic and Molecular Data Centre

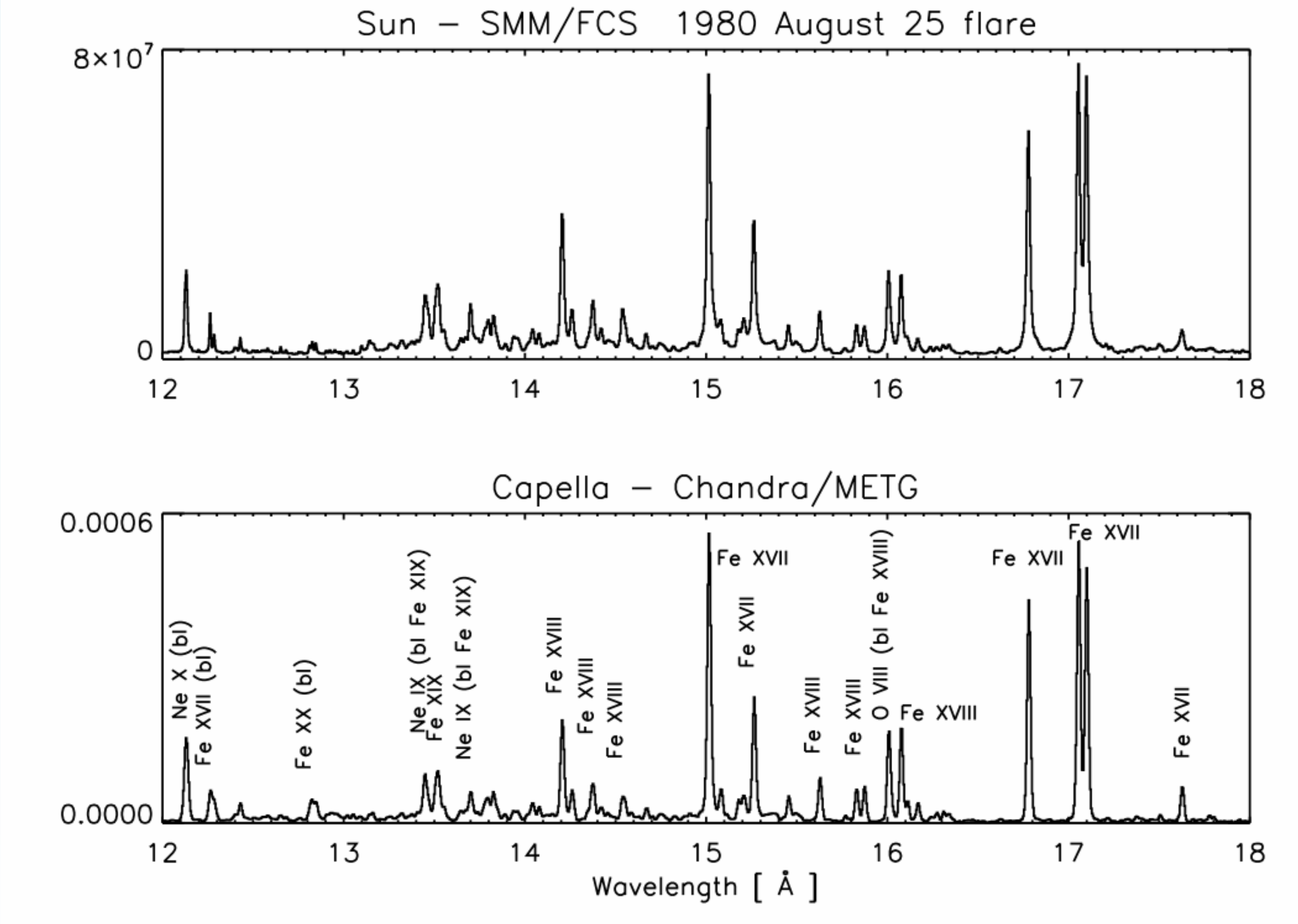
UNIVERSITY OF CAMBRIDGE

From stars …

Del Zanna (1995): first (?) time-resolved EUV spectroscopy of a stellar flare (EUVE satellite)



.. to the Sun ..



To understand active stellar coronae we need to understand solar flares.
We have a long way (cf. chromospheric evaporation, Del Zanna et al. 2011, A&A)

to atoms.

To understand what powers stellar coronae and TRs we need spectroscopy (Jordan)

In optically-thin plasmas (stellar coronae):

$$I \sim n_j\, A_{ji} = \frac{N_j(X^{+m})}{N(X^{+m})}\, A_{ji}\, \frac{N(X^{+m})}{N(X)}\, \frac{N(X)}{N(H)}\, \frac{N(H)}{N_e}\, N_e$$

A-value

A(X)

Level population

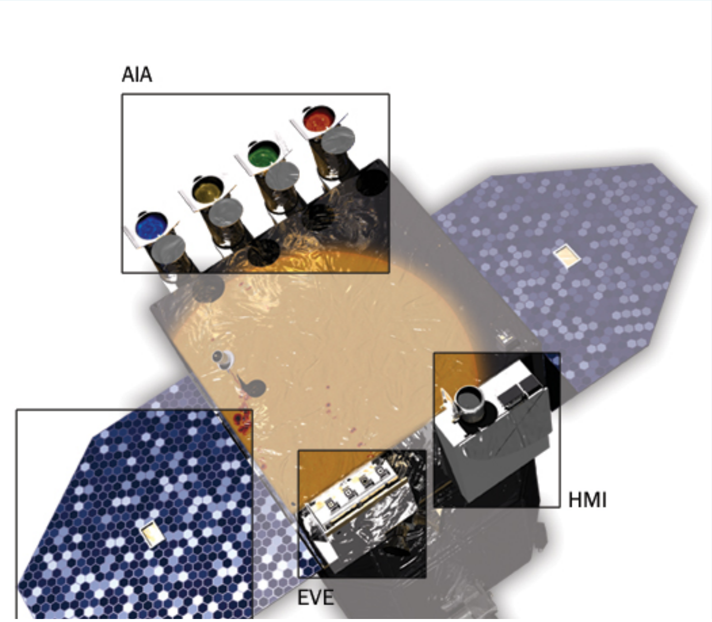
Cross-sections

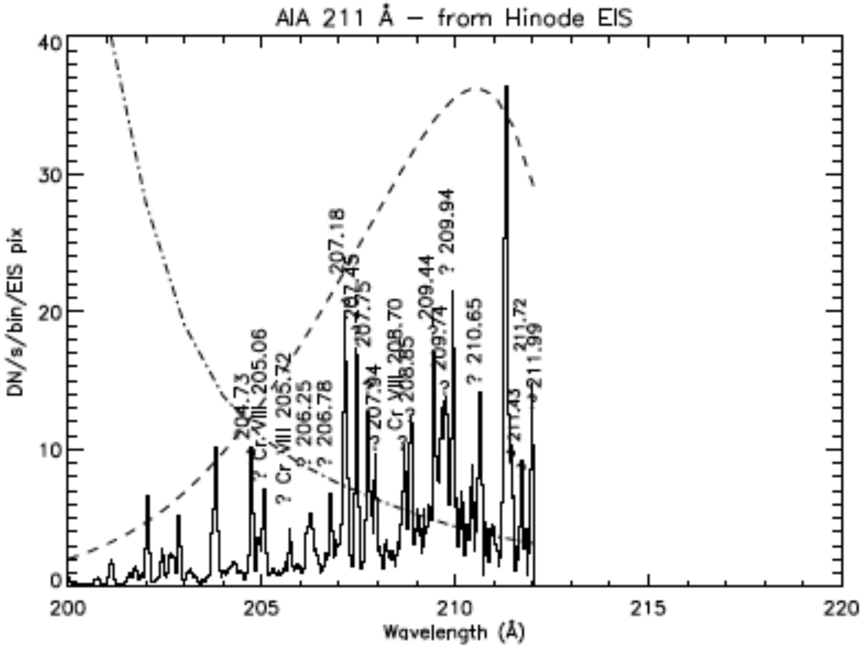
Ion abundance

Cross-sections

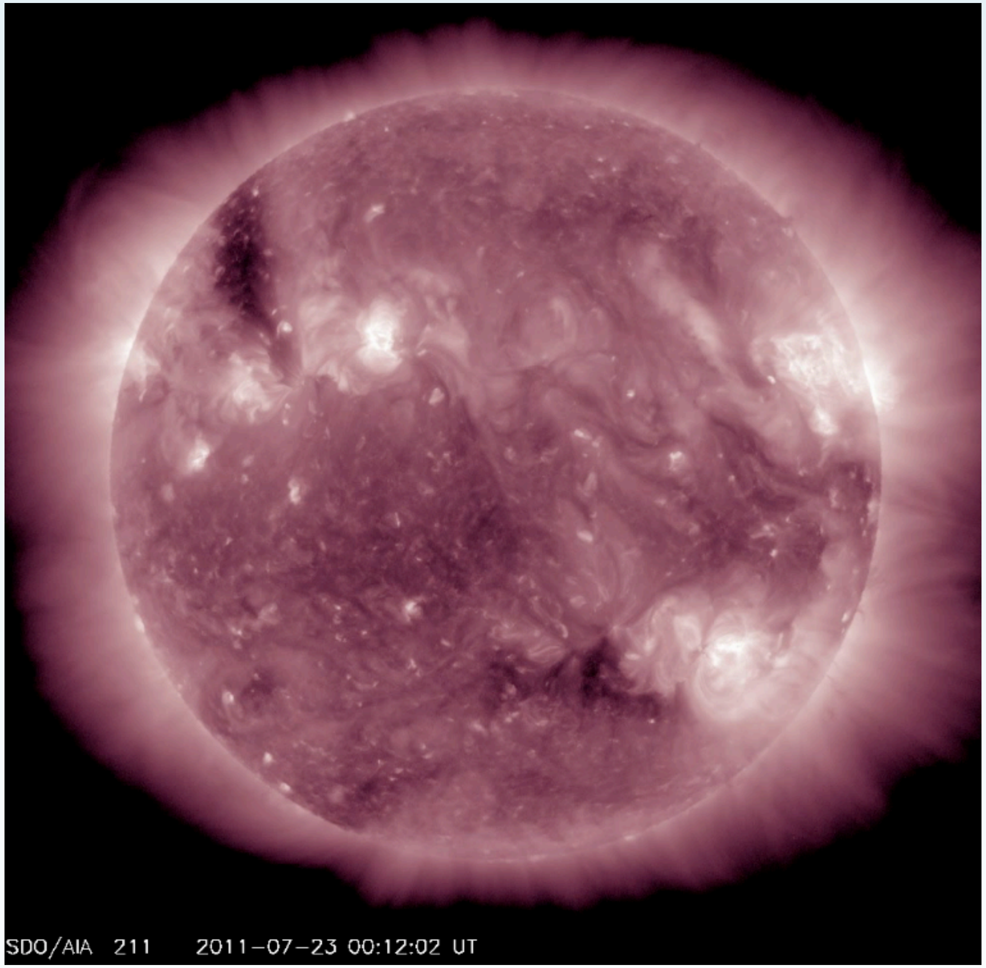
- Good measurements of Ne, Te, A(X), line profiles tied with good modeling.

NASA Solar Dynamics Observatory (SDO) AIA





EUV images every 12s

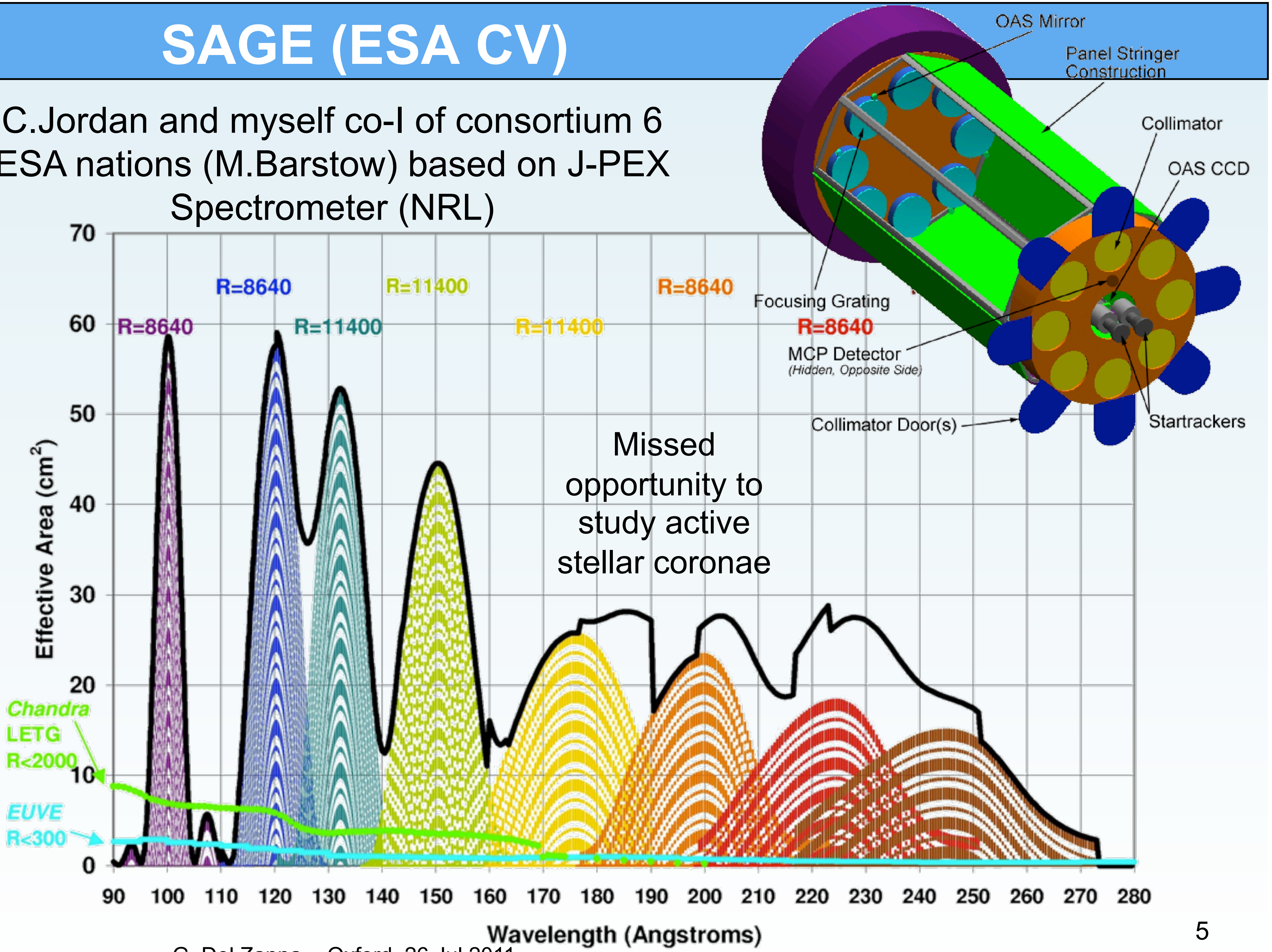


At the footpoints of loops, more than half of the photons in the 211 A band come from unidentified lines !

(Del Zanna O'Dwyer & Mason 2011)

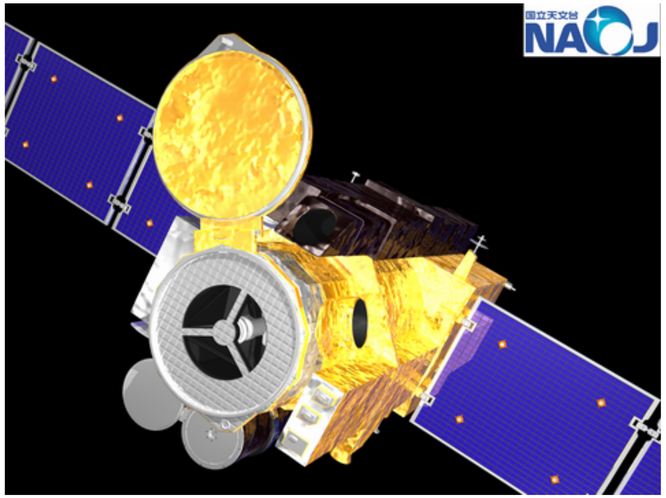
SAGE (ESA CV)

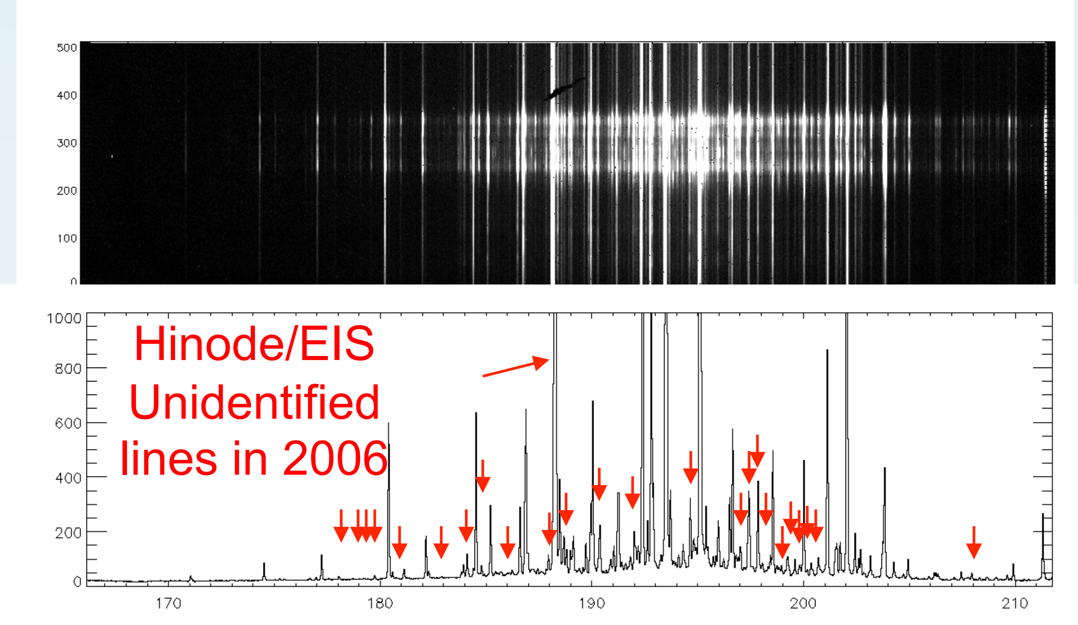
C.Jordan and myself co-I of consortium 6 ESA nations (M.Barstow) based on J-PEX Spectrometer (NRL)



Missed opportunity to study active stellar coronae

Hinode EIS and B.Fawcett's plates





Hinode/EIS Unidentified lines in 2006

B.Fawcett 166 – 212 Angstroms

Resolution almost as good as B.Fawcett's plates.

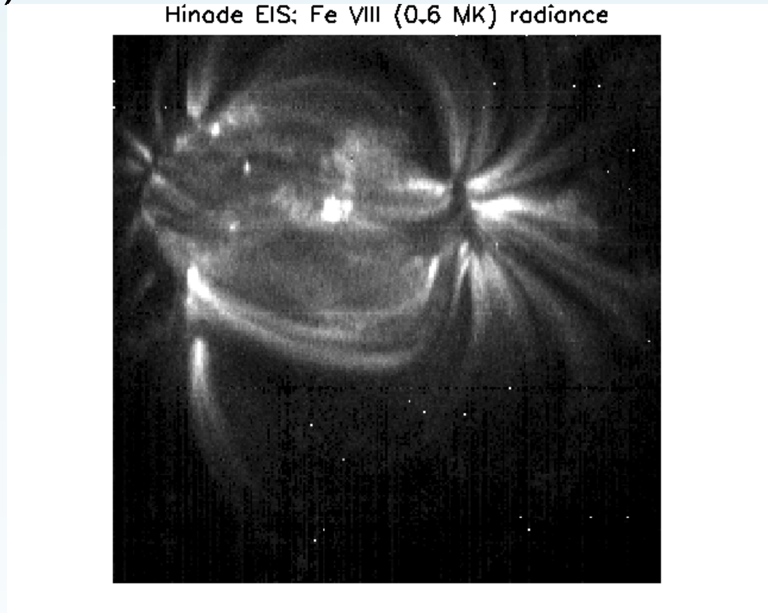
5 m Angstroms accuracy in wavelengths.

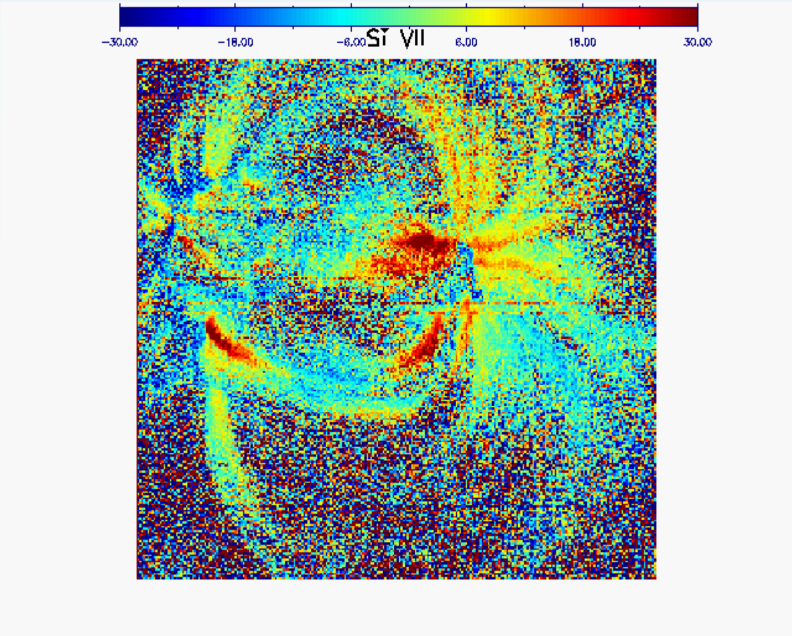
Del Zanna (2011): most brightest coronal lines now identified

Transition region powered by downflows

Hinode/EIS: In the TR, line profiles are red-shifted in both legs of all loops and velocities increase towards the footpoints, at lower T.

(Del Zanna 2007, 2008, confirmed by SOHO/SUMER, Dammasch et al. 2008)





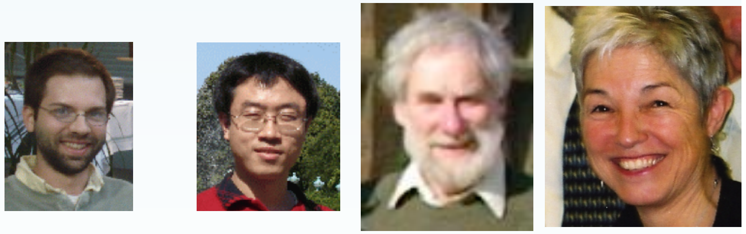
Radiatively cooling and losses supported by an enthalpy flux (Bradshaw 2008).

R-matrix e-ion scattering calculations

R-matrix **electron impact excitation**: (UCL,QUB): Seaton, Burke, Burgess, Storey, Eissner, Berrington, Badnell, etc.
STFC-funded **APAP Network** http://www.apap-network.org/

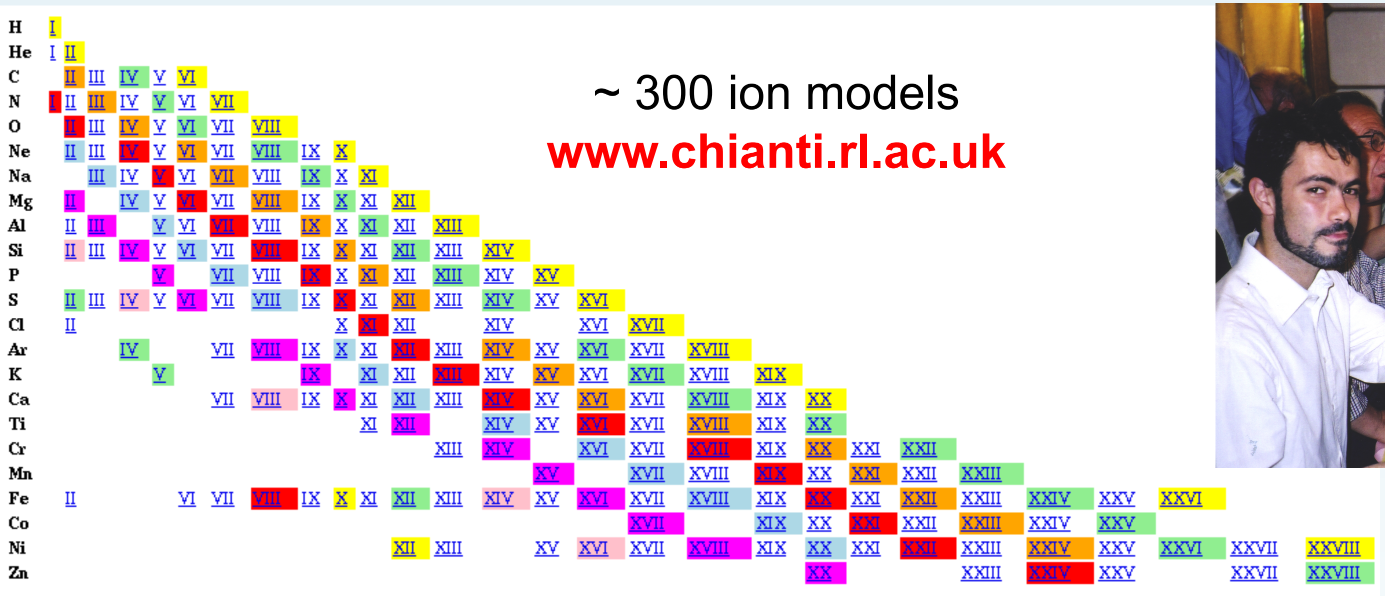
F-like: Witthoeft Whiteford Badnell (2007)
Na-like: Liang, Whiteford,Badnell (2009)
Ne-like: Liang et al. (2010)
Li-like: Liang & Badnell (2010)

- Fe VII: Witthoeft et al. (2008)
- Fe VIII: Griffin et al. (2000)
  Del Zanna (2009)
- Fe IX: Storey et al. (2002)
- Fe X: Del Zanna, Berrington, Mason (2004)
- Fe XI: Del Zanna, Storey, Mason (2010)
- Fe XII: Storey et al. (2005)
- Fe XIII: Storey & Zeippen (2010)
- Fe XIV: Storey et al. (2000); Liang et al. (2010)
- Fe XVIII: Witthoeft et al.(2006).
- Fe XX: Witthoeft, Del Zanna, & Badnell (2007)
- Fe XXIII Chidichimo et al. (2005)



CHIANTI atomic package

CHIANTI Provides all atomic data and programs for collisionally-ionised plasmas.
C. Jordan has always been very supportive – But no UK funding for last 7 years



H	I																											
He	I	II																										
C		II	III	IV	V	VI																						
N	I	II	III	IV	V	VI	VII																					
O		II	III	IV	V	VI	VII	VIII																				
Ne		II	III	IV	V	VI	VII	VIII	IX	X																		
Na			III	IV	V	VI	VII	VIII	IX	X	XI																	
Mg		II		IV	V	VI	VII	VIII	IX	X	XI	XII																
Al		II	III		V	VI	VII	VIII	IX	X	XI	XII	XIII															
Si		II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV														
P					V		VII	VIII	IX	X	XI	XII	XIII	XIV	XV													
S		II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI												
Cl		II								X	XI	XII		XIV		XVI	XVII											
Ar				IV			VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII										
K					V				IX		XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX									
Ca							VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX								
Ti											XI	XII		XIV	XV	XVI	XVII	XVIII	XIX	XX								
Cr													XIII	XIV		XVI	XVII	XVIII	XIX	XX	XXI	XXII						
Mn															XV		XVII	XVIII	XIX	XX	XXI	XXII	XXIII					
Fe		II				VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI		
Co																	XVII		XIX	XX	XXI	XXII	XXIII	XXIV	XXV			
Ni												XII	XIII		XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI	XXVII	XXVIII
Zn																				XX			XXIII	XXIV	XXV		XXVII	XXVIII

~ 300 ion models

www.chianti.rl.ac.uk

V.6 (Dere et al.2009) contained **new ionization and recombination rates**.
V.7 (Landi et al. 2011), Aug 2011, new atomic data for many ions.
V.8 will introduce new format.
Atomic data included other spectral codes. (XSTAR, CLOUDY, MOCASSIN, ATOMDB, XSPEC, ISIS, PINTofALE). Over 1000 direct citations, few 100s/year

Have we made it too easy ? ***`CHIANTI does not have a line therefore there is no blend’***

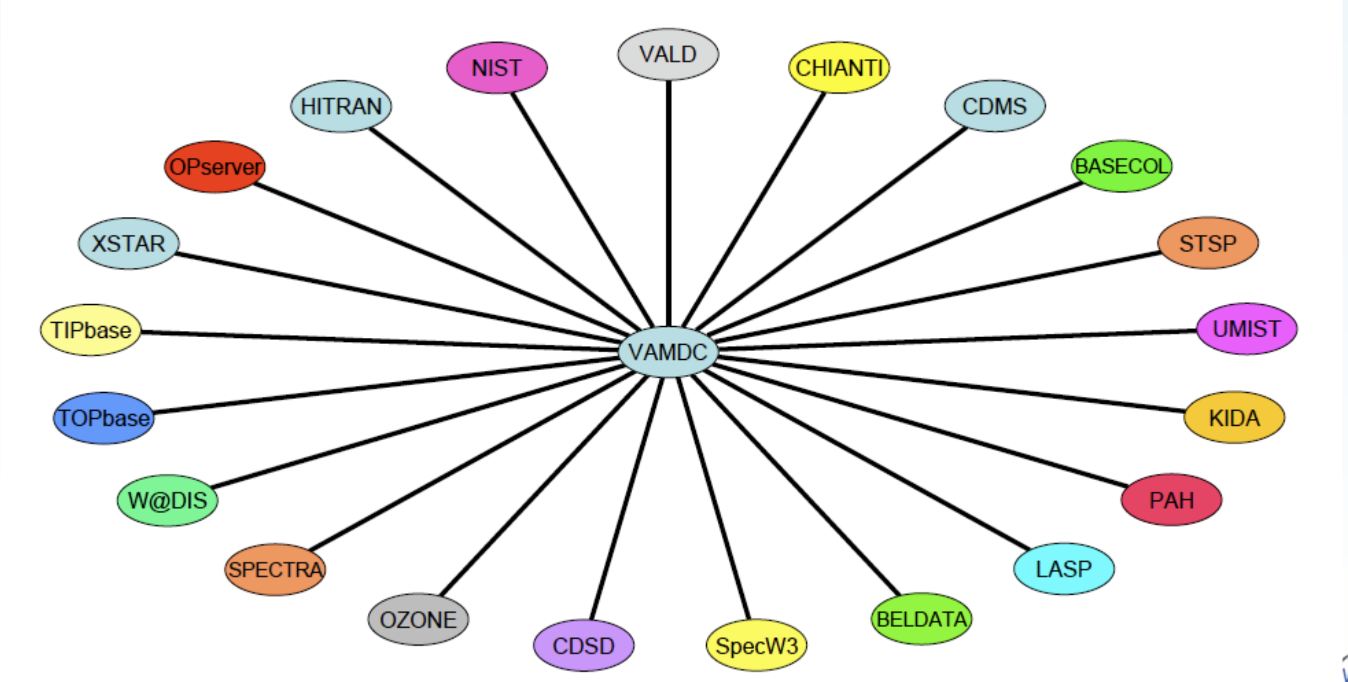
Virtual Atomic and Molecular Data Center

-Giulio Del Zanna & Helen Mason (Cambridge) with IoA and MSSL collaboration

-All the BASIC CHIANTI DATA in MySQL, queried via a web portal or workbench.
-DERIVED DATA (modelling): Python scripts to read the CHIANTI VAMDC

How can different databases be easily compared ?
Multiple calculations. CHIANTI policy is to select one.

Appropriate references to original calculation lost.



www.vamdc.eu

VAMDC
Virtual Atomic and Molecular Data Centre

Benchmarking atomic data (Del Zanna 2003-)

Werner Eissner

1) Find the best atomic structure with appropriate CI (and semi-empirical corrections)
2) Compare observed (beam-foil spectroscopy, Elmar Traebert et al.) and theoretical lifetimes and branching ratios.
3) Calculate e excitation rates (R-matrix) and build ion model to calculate line intensities.
4) compare observed and theoretical wavelengths and intensities for low- and high-densities using the emissivity ratios:

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

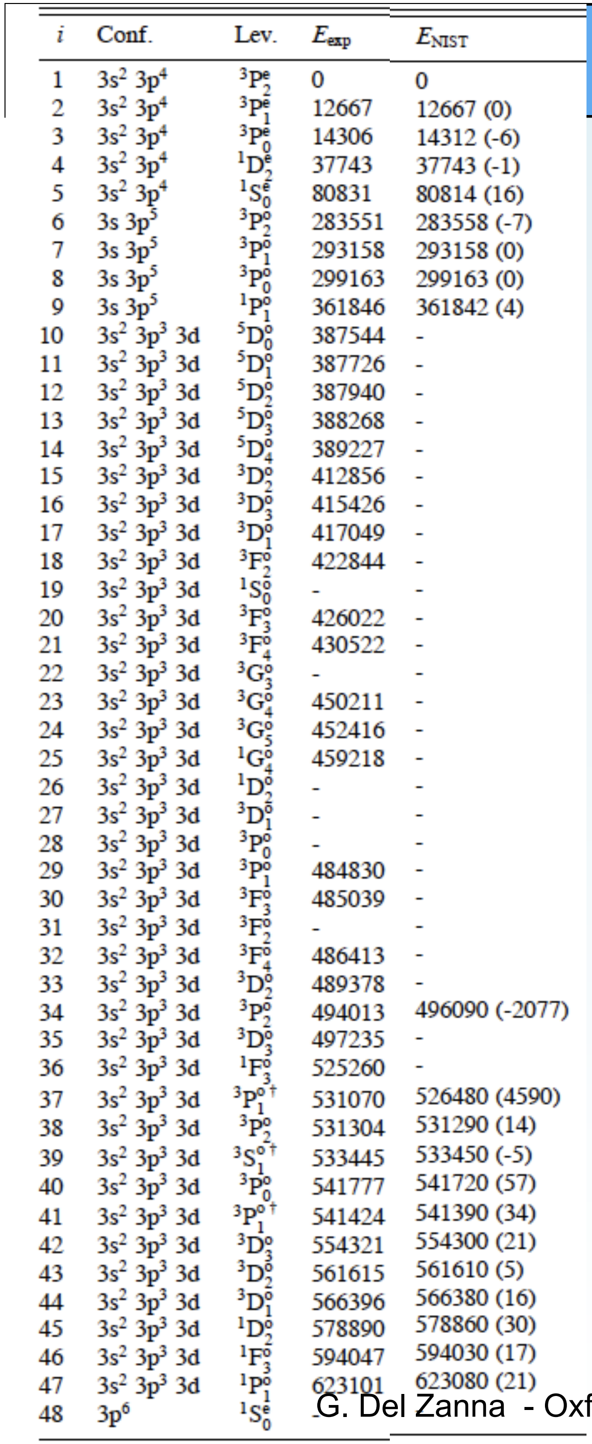
5) Try to identify all the brightest lines, using laboratory and astrophysical spectra (best solar before 1973).

RESULTS:

a large number of new identifications, new level energies, revised wavelengths (with uncertainties).

New Ne, Te diagnostic applications

Fe XI



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	$3p^6$	$^1S^e_0$	-	[illegible]

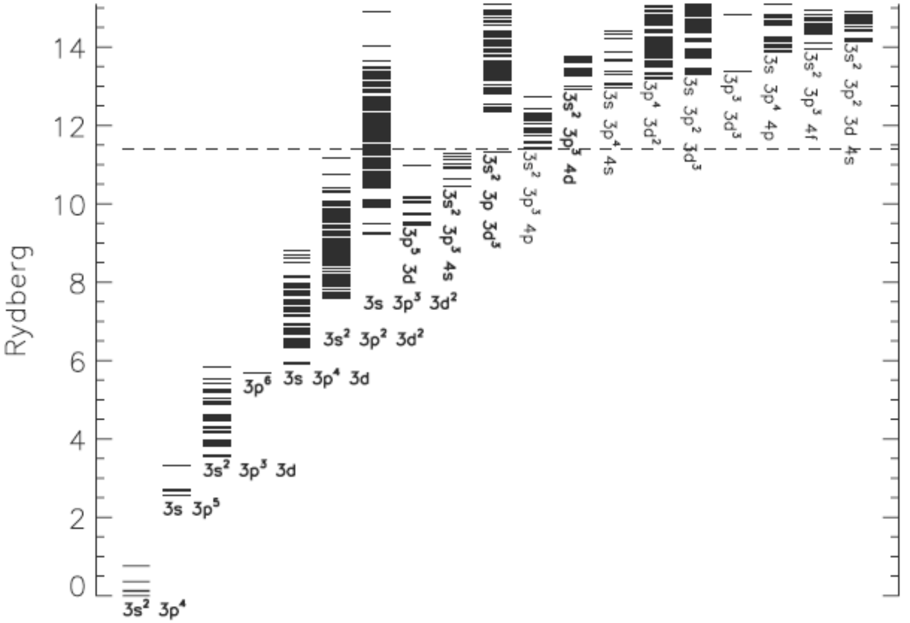
Most 3d levels were not known.
Difficulty in the structure calculations.

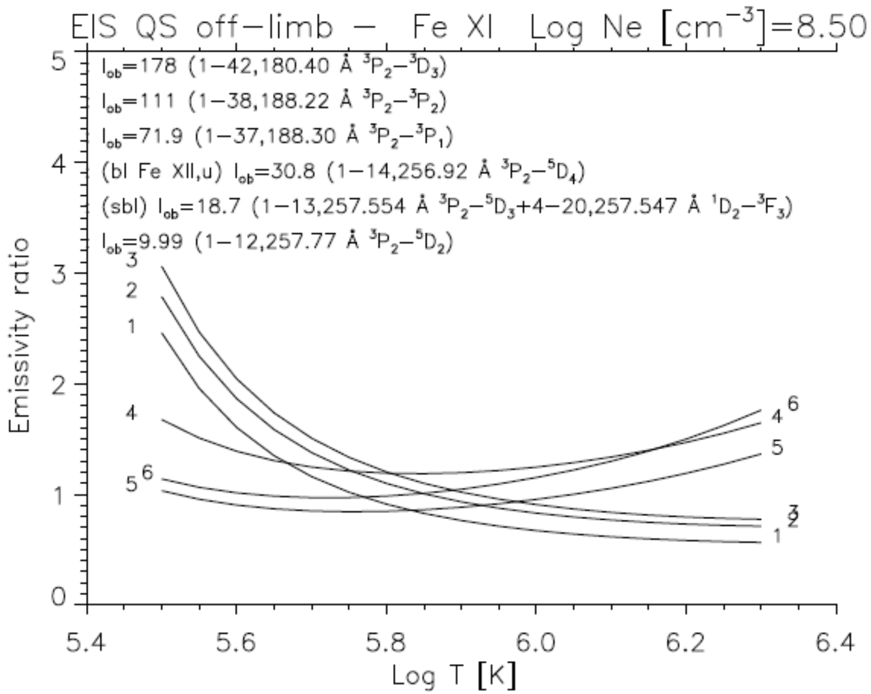
Fe XI – after 6 years..

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]

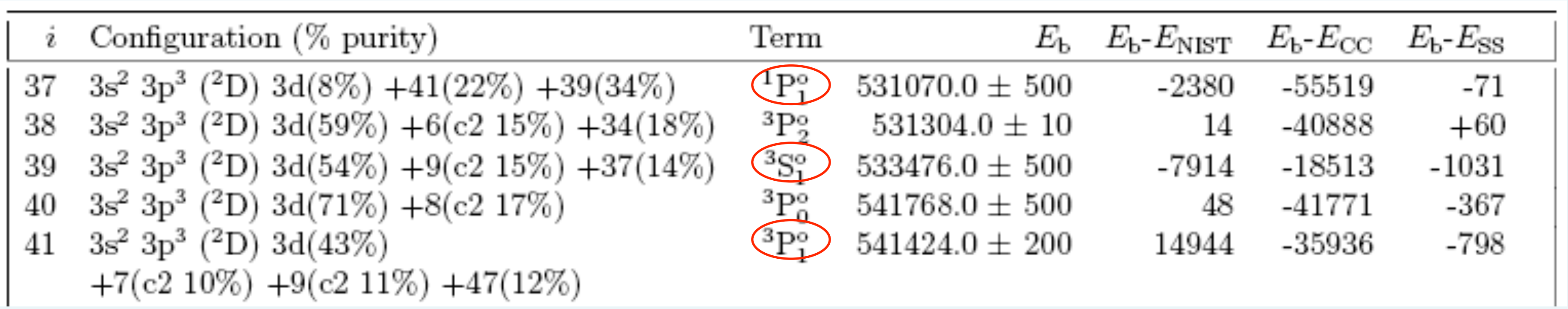




◆Target: 13 configurations,145 LS terms

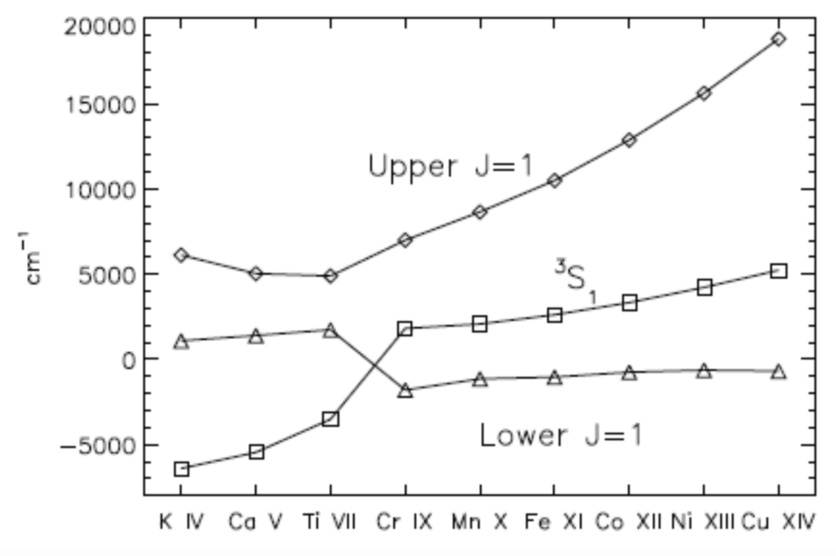
New Te diagnostics

Fe XI



i	Configuration (% purity)	Term	E_b	E_b-E_{NIST}	E_b-E_{CC}	E_b-E_{SS}
37	$3s^2\ 3p^3\ (^2D)\ 3d(8\%)\ +41(22\%)\ +39(34\%)$	$^1P^o_1$	531070.0 ± 500	-2380	-55519	-71
38	$3s^2\ 3p^3\ (^2D)\ 3d(59\%)\ +6(c2\ 15\%)\ +34(18\%)$	$^3P^o_2$	531304.0 ± 10	14	-40888	+60
39	$3s^2\ 3p^3\ (^2D)\ 3d(54\%)\ +9(c2\ 15\%)\ +37(14\%)$	$^3S^o_1$	533476.0 ± 500	-7914	-18513	-1031
40	$3s^2\ 3p^3\ (^2D)\ 3d(71\%)\ +8(c2\ 17\%)$	$^3P^o_0$	541768.0 ± 500	48	-41771	-367
41	$3s^2\ 3p^3\ (^2D)\ 3d(43\%)$ $+7(c2\ 10\%)\ +9(c2\ 11\%)\ +47(12\%)$	$^3P^o_1$	541424.0 ± 200	14944	-35936	-798

Main problems with three very mixed J=1 levels, giving rise to the strongest spectral lines observed in the EUV by Hinode
Found significant problems with all previous calculations.

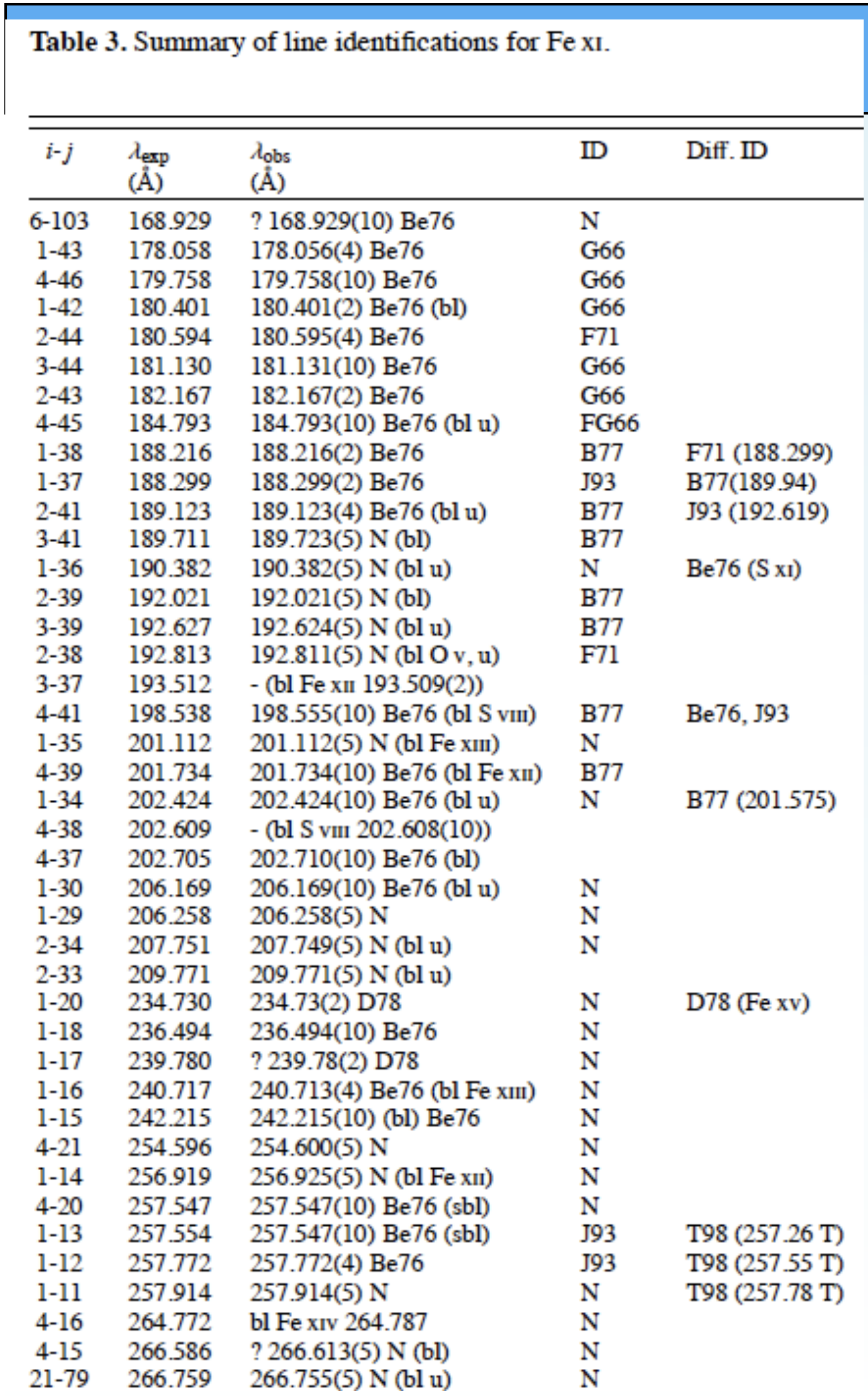


Needed to study all ions along the sequence.
Ekefors (1931): K IV, Ca V best paper !

Fe XI

Benchmark:Del Zanna (2010)

31 (out of 60) new line identifications



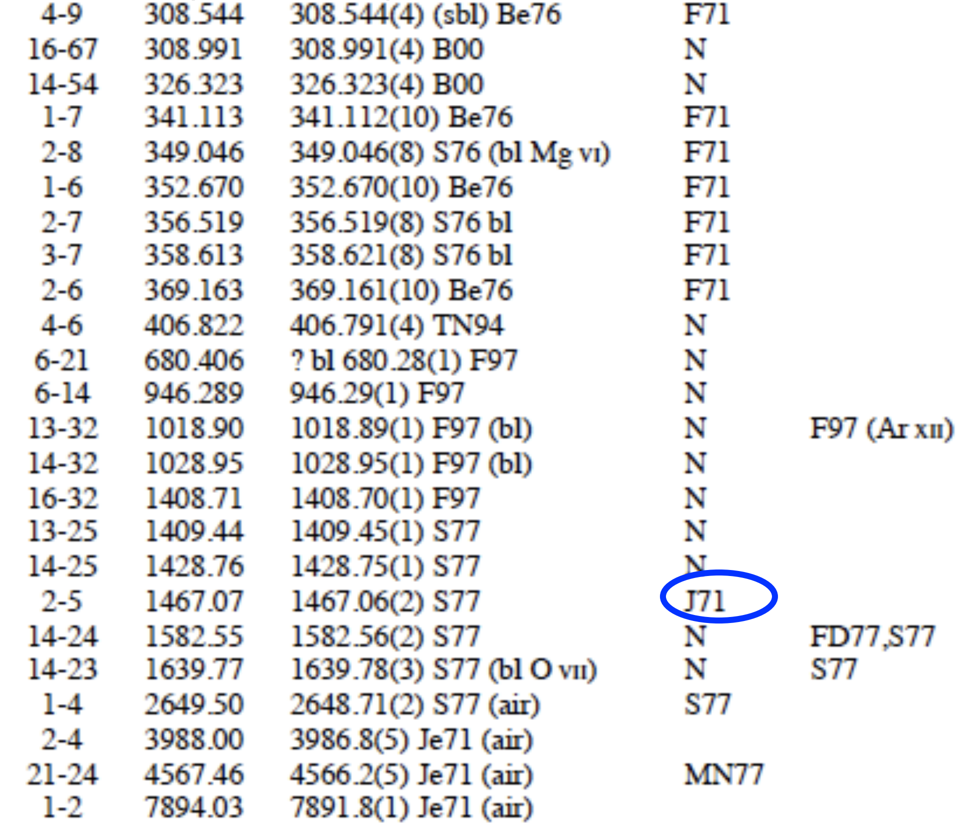
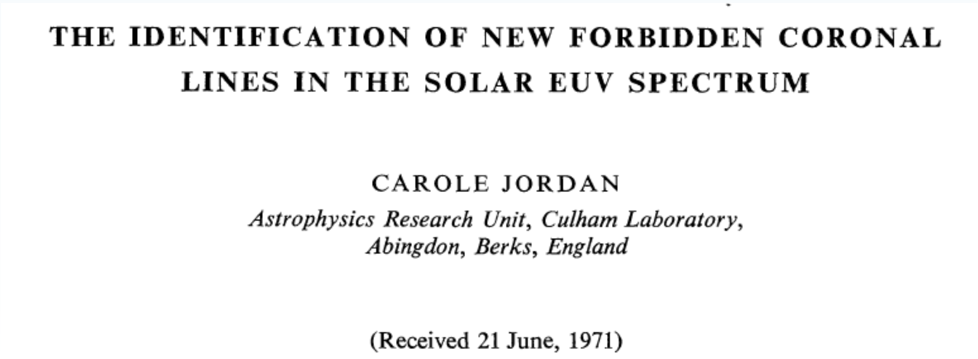


Table 3. Summary of line identifications for Fe xi.

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)		



THE IDENTIFICATION OF NEW FORBIDDEN CORONAL LINES IN THE SOLAR EUV SPECTRUM

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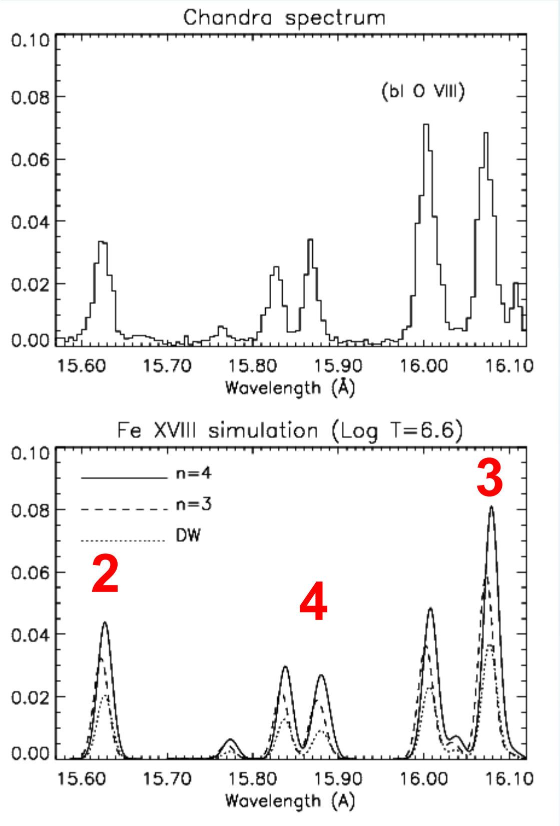
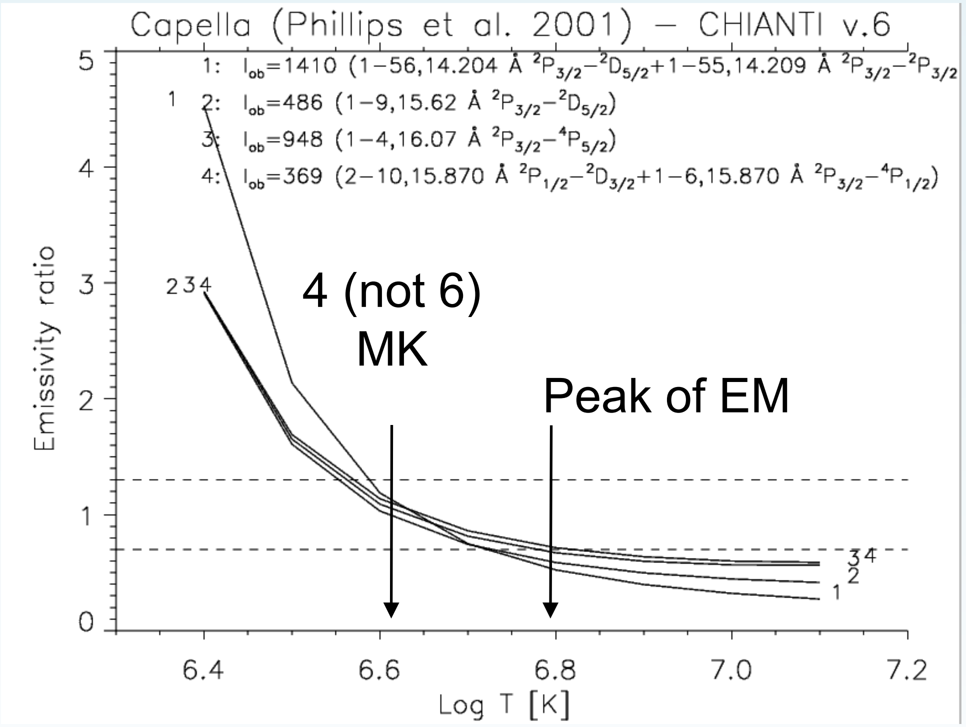
Measuring Te in stellar coronae - Fe XVIII

First R-matrix e- scattering calculation by Witthoeft, Badnell, Del Zanna et al. (2006) solved the problem with the strong 3s--> 2p transitions .



$2s^2\ 2p^4\ 3s \;\text{-->}\; 2s^2\ 2p^5$



4 (not 6) MK

Peak of EM

Same issues with Fe XVII (Del Zanna 2011, A&A)

Benchmarking atomic data for Iron ions

- Fe VII: Del Zanna (2009a) 31/ 53 new EUV (160-300 A) IDs, new Te diagnostics
- Fe VIII: Del Zanna (2009b) 9/34 new EUV IDs, new Te diagnostics

- Fe X: Del Zanna, Berrington, Mason (2004) 9/45 new IDs
- Fe XI: Del Zanna (2010) 31/60 new IDs, new Te diagnostics
- Fe XII: Del Zanna & Mason (2005) 21/58 new IDs
- Fe XIII: Del Zanna (2011a) 13/41 new EUV IDs

- Fe XIV: Del Zanna (2011b)
- Fe XVII: Del Zanna & Ishikawa (2009) 16/50 new IDs (40-400 A), Del Zanna (2011): `new' Te diagnostics

- Fe XVIII: Del Zanna (2006) new IDs, new Te diagnostics
- Fe XX: Witthoeft, Del Zanna, Badnell (2007)

- Fe XXIII Del Zanna et al. (2005) new Ne,Te diagnostics
- Fe XXIV Del Zanna (2006) new Ne,Te diagnostics
-

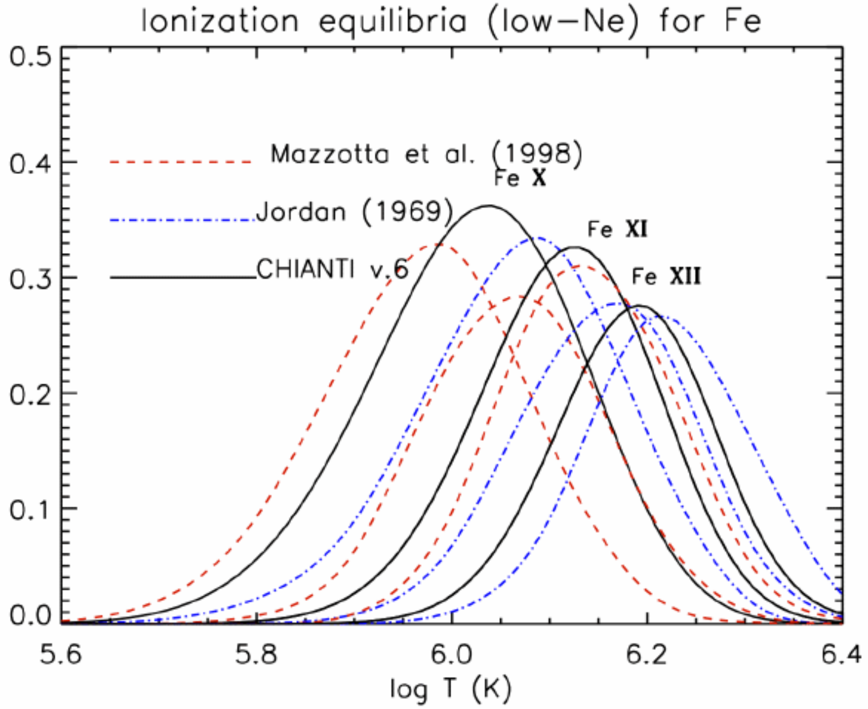
Ionization equilibrium

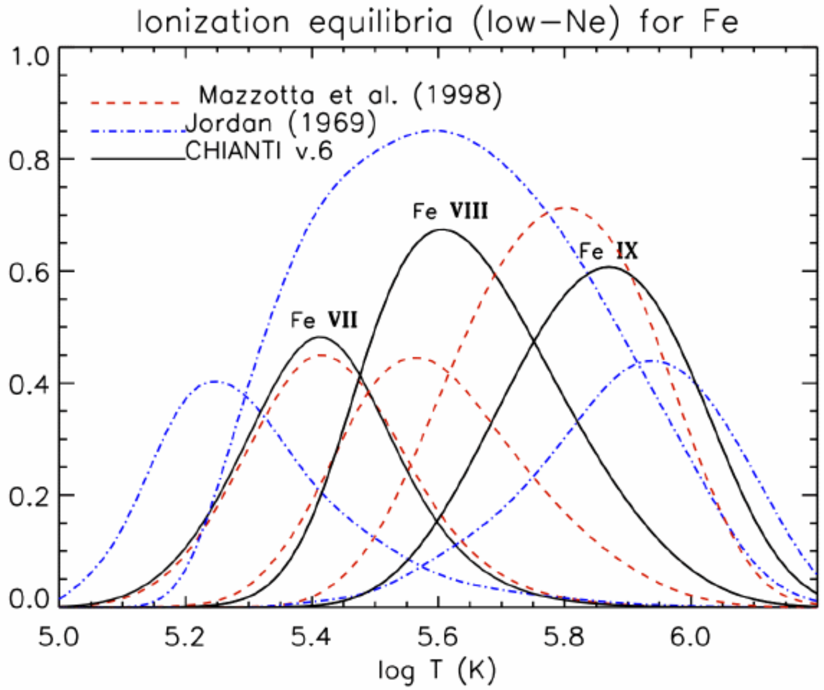
Jordan (1969), largely based on Seaton & Burgess

CHIANTI v.6 (Dere et al. 2009) based on ab-initio calculations of cross-sections:

1) **Direct-ionization by electron impact**: Dere (2007)
2) **Radiative recombination**: Badnell (2006).
3) **Dielectronic recombination**: Badnell et al. (2003+ a number of papers).

However, density and time-dependent ionization effects still to be properly included (Cambridge, Armagh, also see Jaroslav's talk)


Ionization equilibria (low−Ne) for Fe

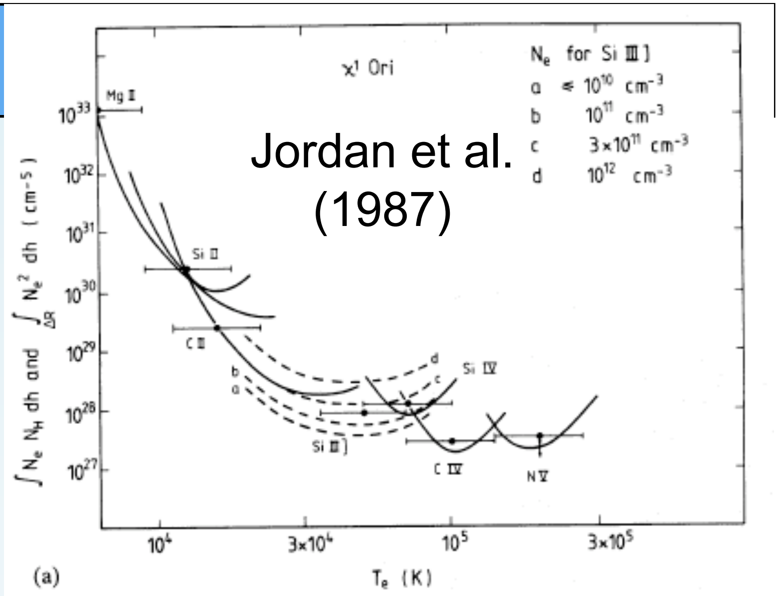

Ionization equilibria (low−Ne) for Fe

EM loci

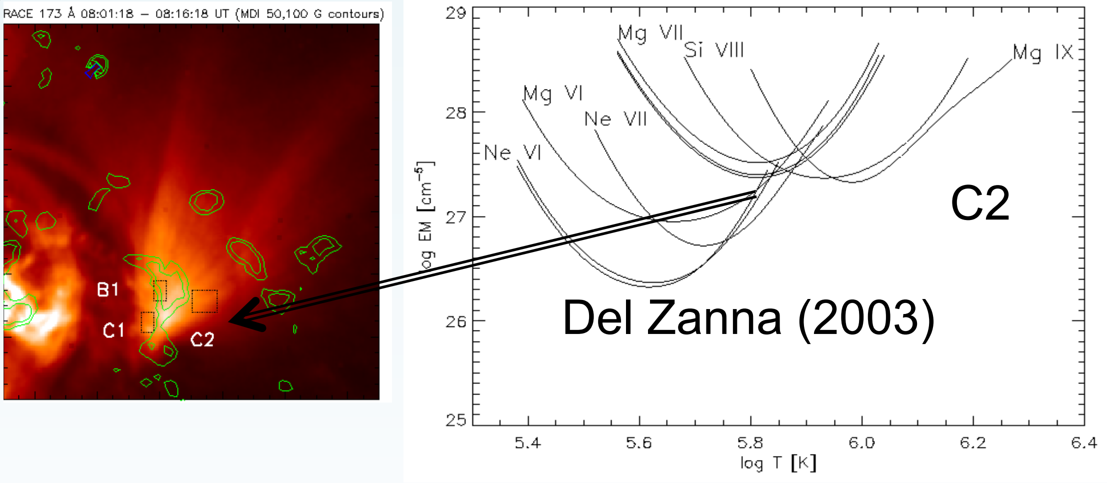
$$I_{ji} = \int f\, Ab(Y)\, G_{ji}(T_e)\, N_e^{2}\, dh \cong$$

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

$$EM = \int N_e(h)^2\, dh \qquad \frac{Iobs}{Ab(Y)\; Gji(Te)}$$


Jordan et al. (1987)

Del Zanna (2003) re-introduced the EM loci method (Strong 1978) to AR loops. Isothermal !


C2

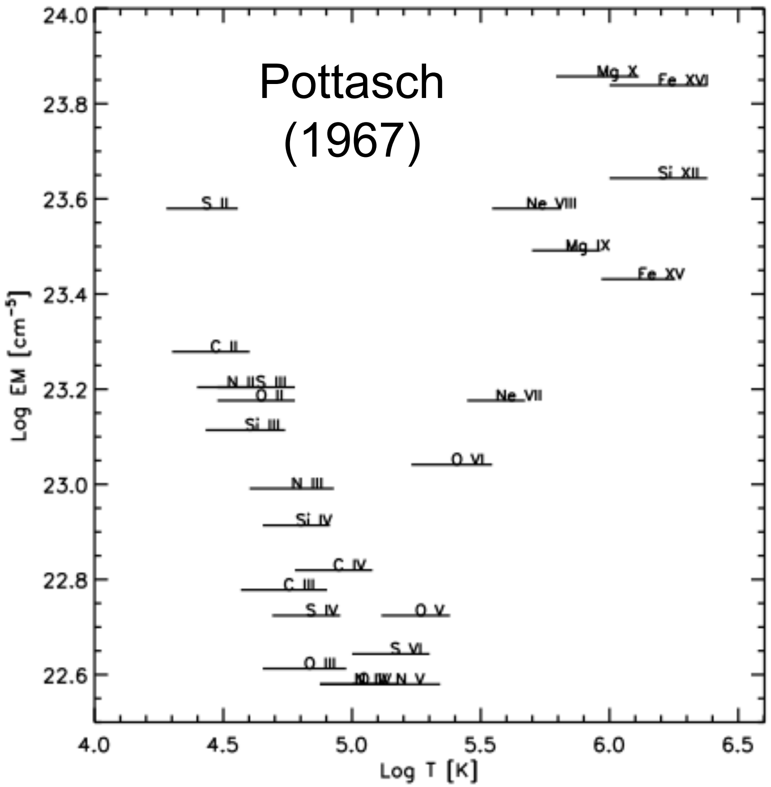
Del Zanna (2003)

ARs are organised into isothermal structures.
Warmer and cooler loops are intermingled (Del Zanna et al. 2006)

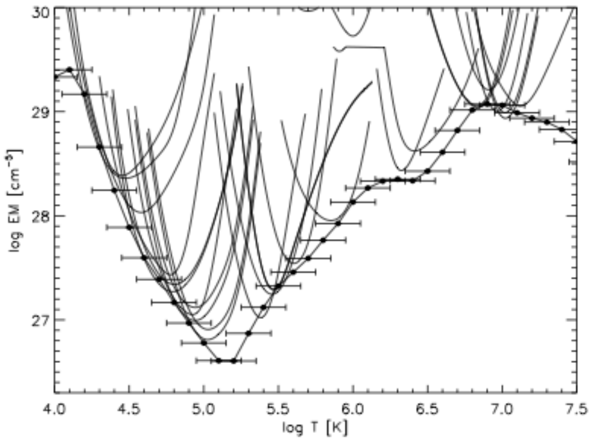
The problem of the ‘anomalous’ ions

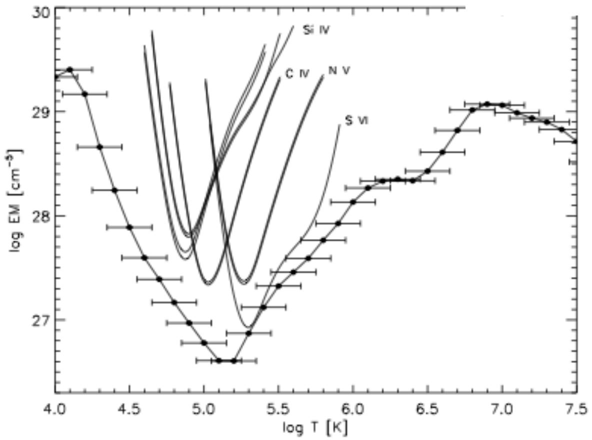
Anomalous EM in Li and Na isoelectronic sequences (e.g. Burton et al. 1971, Dupree 1972, Judge et al. 1995; Del Zanna 1999;Del Zanna et al. 2001,2002).

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



Li-, Na-like



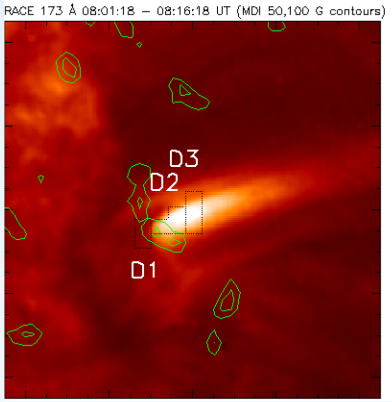


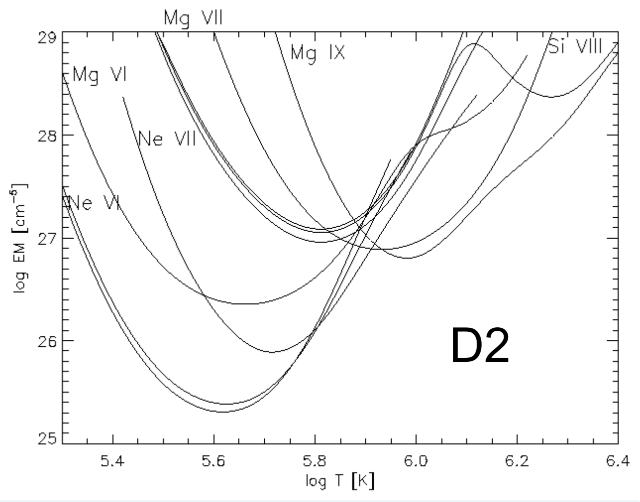
Li-like N V and C IV are underestimated by factors of 3 and 10, while those of Ne VIII and Mg X are overestimated by factors of 5 and 10,respectively.

FIP effect in AR loops ?

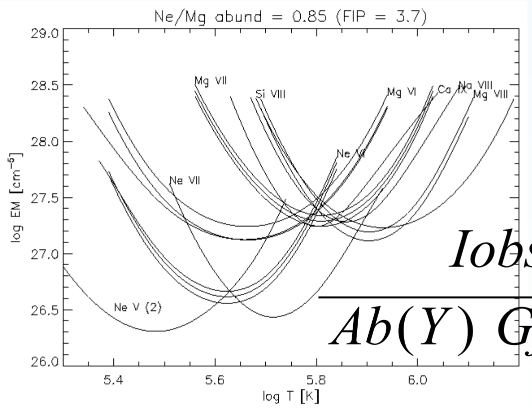
Potentially an important diagnostic (M. Laming).

CDS: Mg/Ne photospheric abundances
(EM loci, Del Zanna 2003).

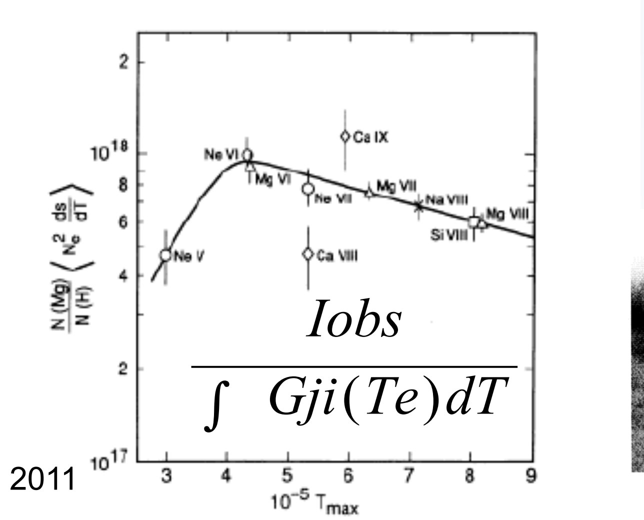




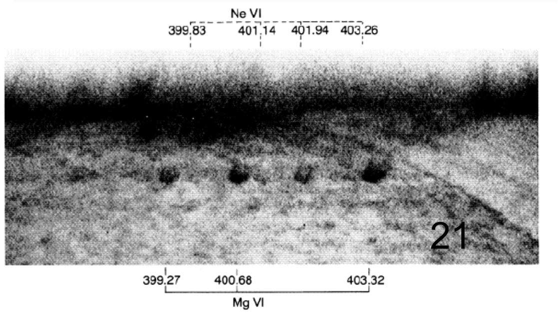
Work using Skylab data overestimated (~4) the Mg/Ne FIP bias.
The Widing & Feldman (1993) method assumes a continuous DEM
(Del Zanna 2003)



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



$$\frac{Iobs}{\int\ Gji(Te)dT}$$



Conclusions

We now often have excellent agreement (within 10%) between theoretical and observed line intensities for stellar coronae.

We have made a great progress, but we are still faced with many old issues..

To understand what powers stellar coronae and TR we need more spectroscopy and meetings like this one !

Long life to all - Thank you