Modelling Low Charge Ions in the Solar Atmosphere

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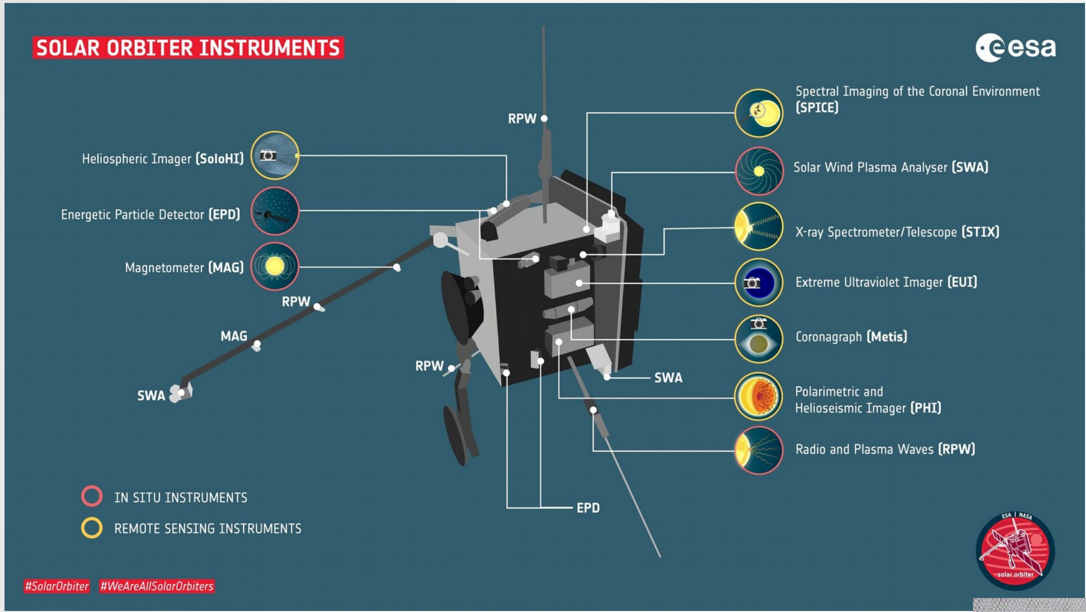
MNRAS 2020, 497, 1443; MNRAS 2021a, 503, 1976; MNRAS 2021b (submitted)

Modelling Oxygen Ion Populations

Contents

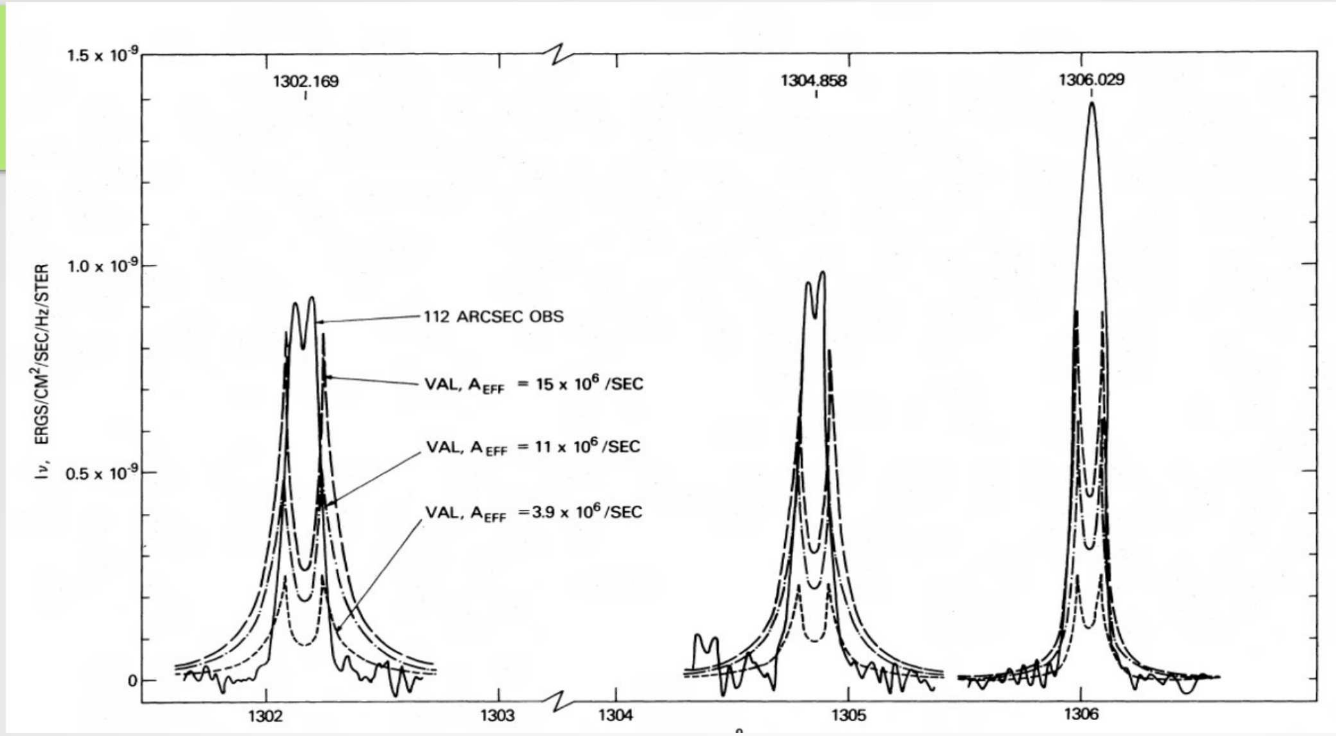
Background



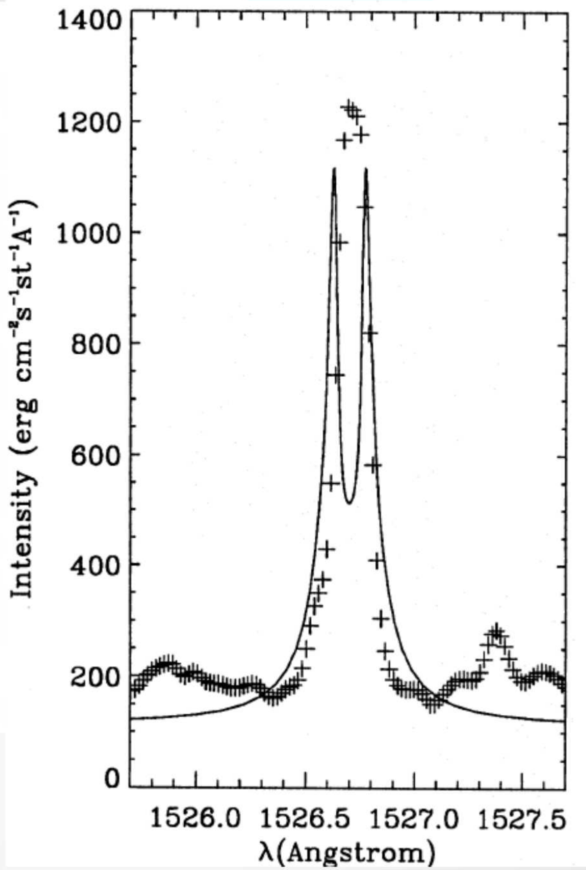
Solar Orbiter – SPICE (Spectral Imaging in Coronal Environment)

Observes – 704-790 Å and 973-1049 Å, most of which are transition region lines

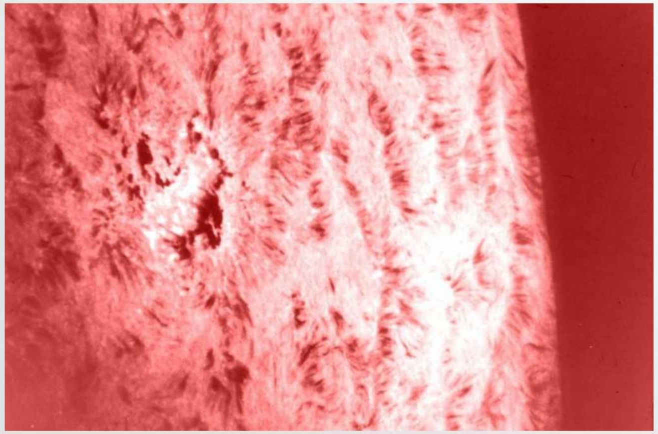
For oxygen, will see:
O I – 1028-1048 Å
O II – 718 Å
O III – 704 Å
O IV – 787, 790 Å
O V – 760 Å
O VI – 1031, 1037 Å



O I resonance lines observed (solid) and theoretical
Skelton D. L., Shine R. A., 1982, ApJ, 259, 869



Si II line observed (crosses) and theoretical
Lanzafame A. C., 1994, A&A, 287, 972



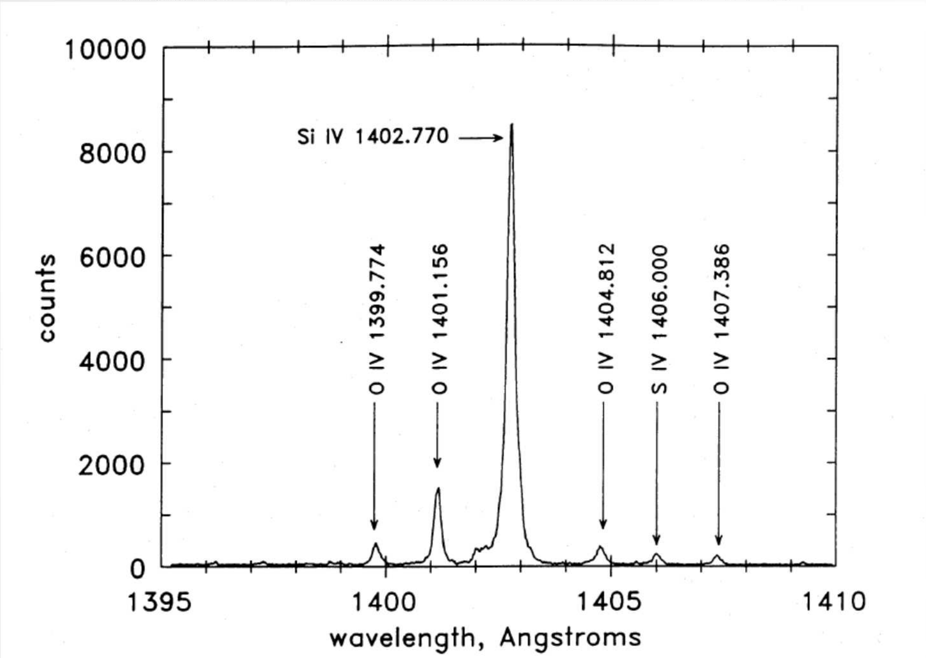
Chromosphere (6000-25000K) – Time-dependent ionisation, radiation hydrodynamics, photo-induced processes, charge transfer, inelastic collisions with hydrogen.

Background

Corona (6x10^5-3x10^6 K) – steady state equilibrium, independent atom models, ground level ionisation and recombination

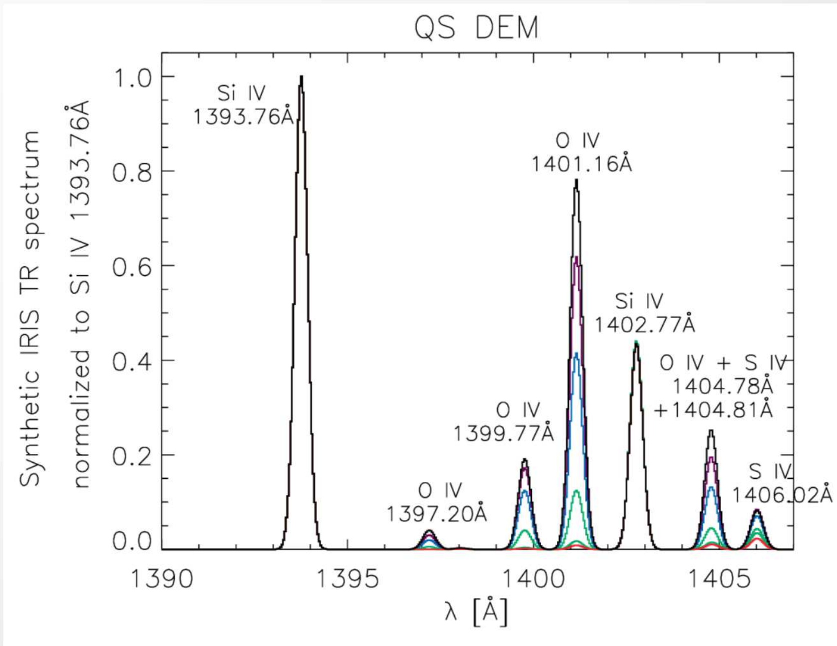
Included in CHIANTI (Del Zanna et al. 2021, ApJ 909, 38), CLOUDY (Ferland G.J. et al. 2017, RmxAA, 53, 385), for example.

Observed intensities from HRTS



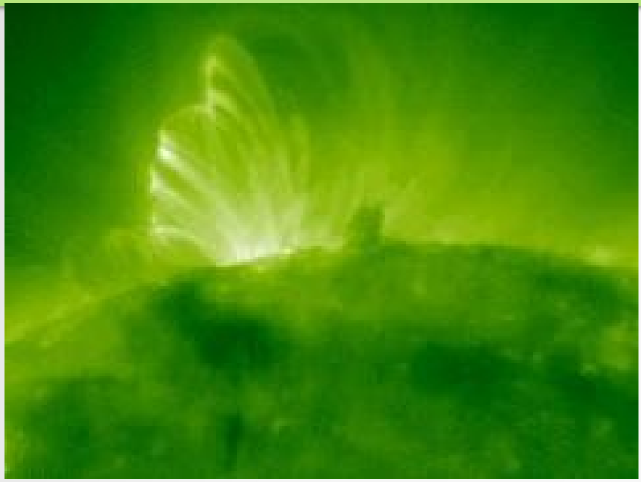
Brekke P., 1993, ApJS, 87, 443

Predicted intensities from modelling

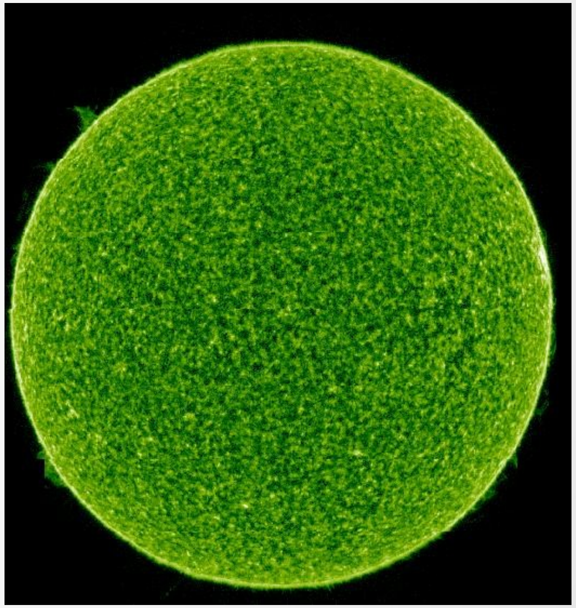


Dudik J., et al., 2014, ApJL, 780, L12

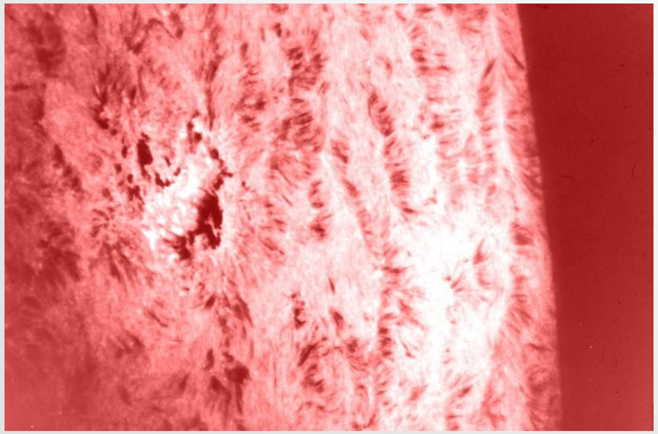
Background



Corona ($6x10^5$-$3x10^6$ K) – steady state equilibrium, independent atom models, ground level ionisation and recombination



Transition region (25000-$6x10^5$K) -
?



Chromosphere (6000-25000K)– Time-dependent ionisation, radiation hydrodynamics, photo-induced processes, charge transfer, inelastic collisions with hydrogen.

Modelling Oxygen Ion Populations

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Modelling

Solar atmosphere temperature and density

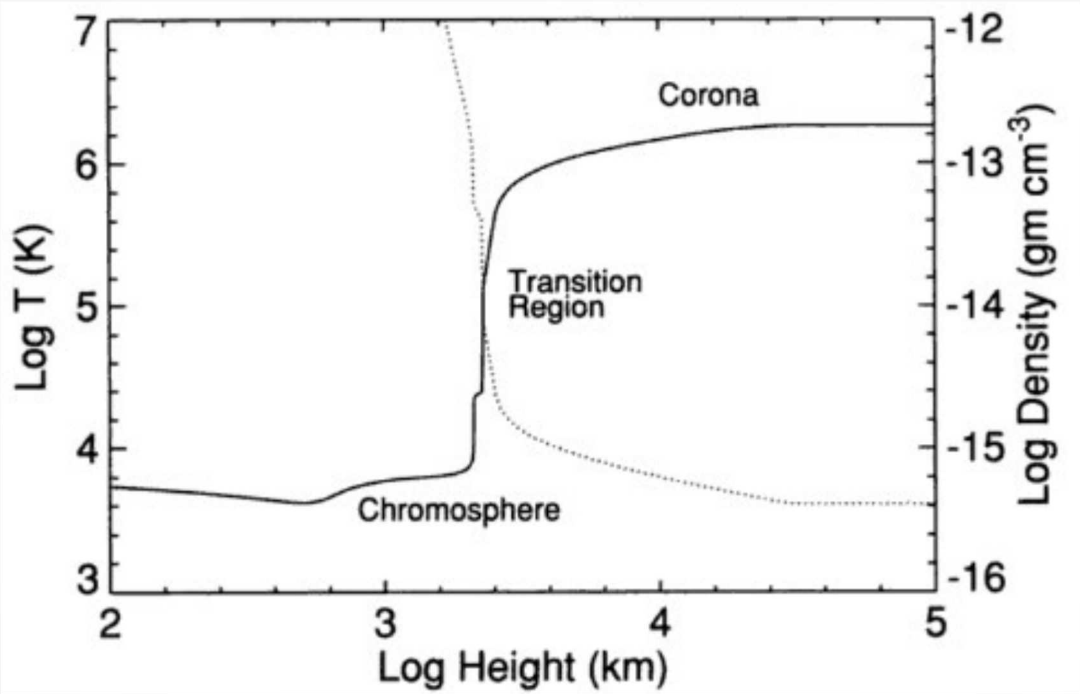
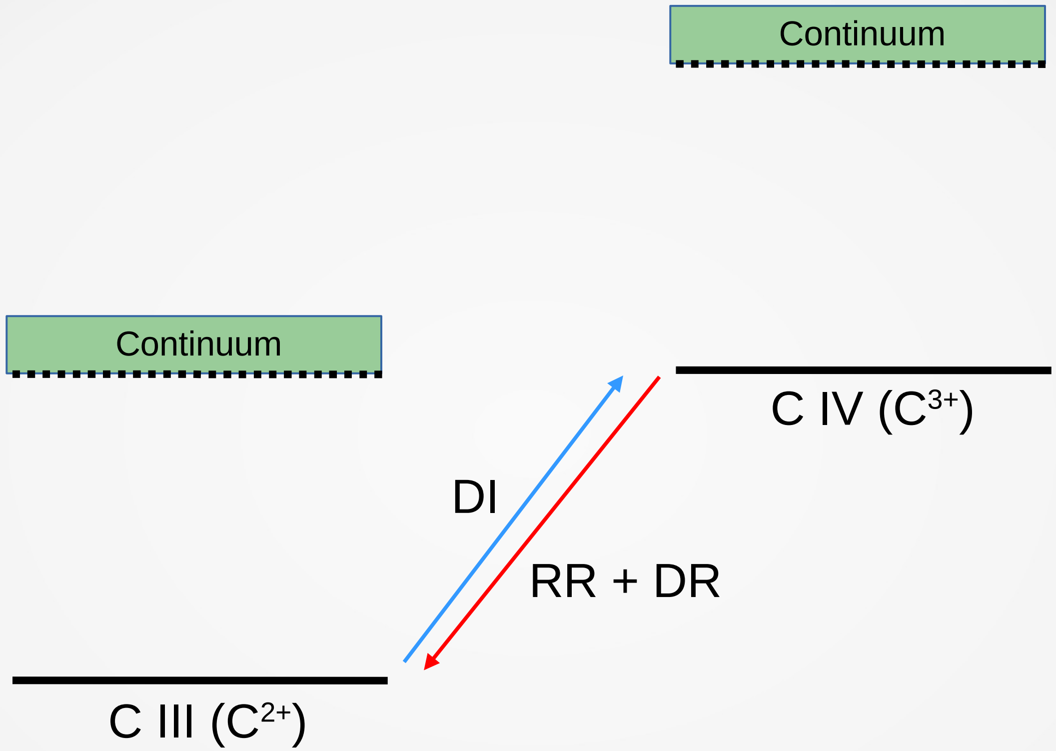


Image from J.T. Mariska, *The Solar Transition Region*, CUP, 1992

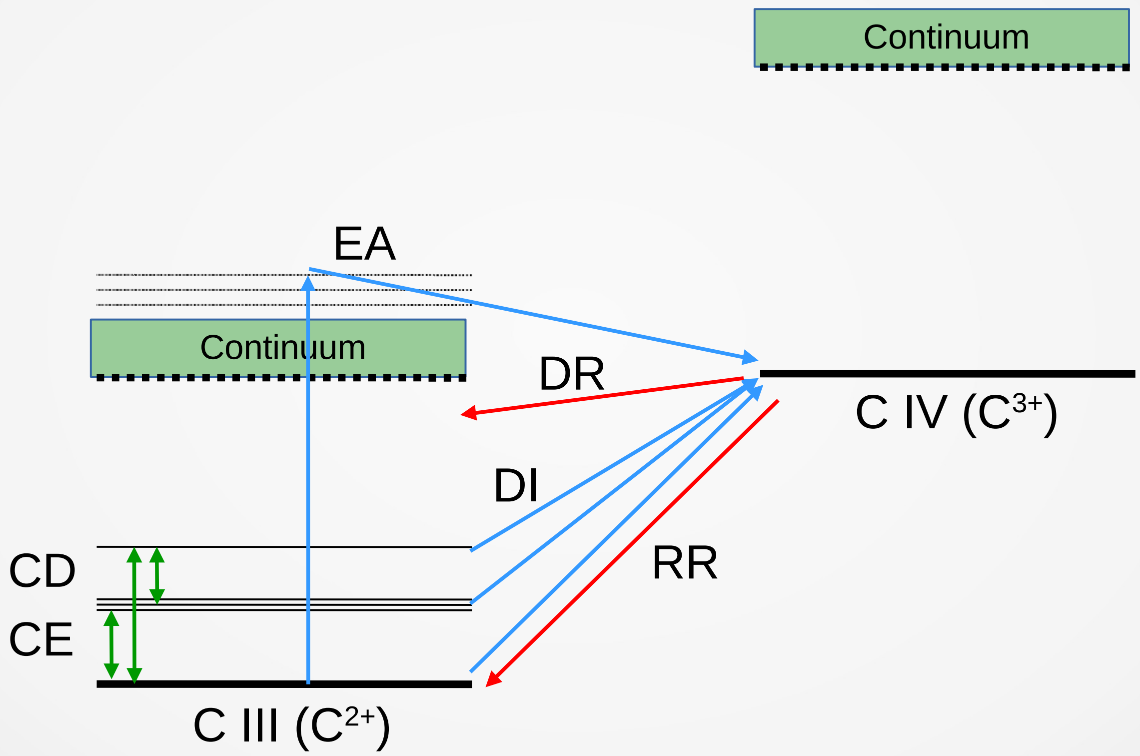
Modelling: Coronal Approximation



DI – Direct Ionisation
RR – Radiative Recombination
DR – Dielectronic Recombination

$$\frac{\mathrm{dN}^z}{\mathrm{dt}} = R^{z+1} N^{z+1} - S^z N^z = 0$$

Modelling: Level Resolved



DI – Direct Ionisation
RR – Radiative Recombination
CE/CD – Collisional Excitation/De-excitation

EA – Excitation-Autoionisation
DR – Dielectronic Recombination

Modelling: Dielectronic Recombination

Effect of density on DR rates demonstrated by Burgess & Summers (1969), ApJ, 157, 1007.

- DR suppression calculated by scaling rate at given density to rate at lowest density.

- Uses tables given in Summers H.P. (1974), MNRAS, 169, 663.

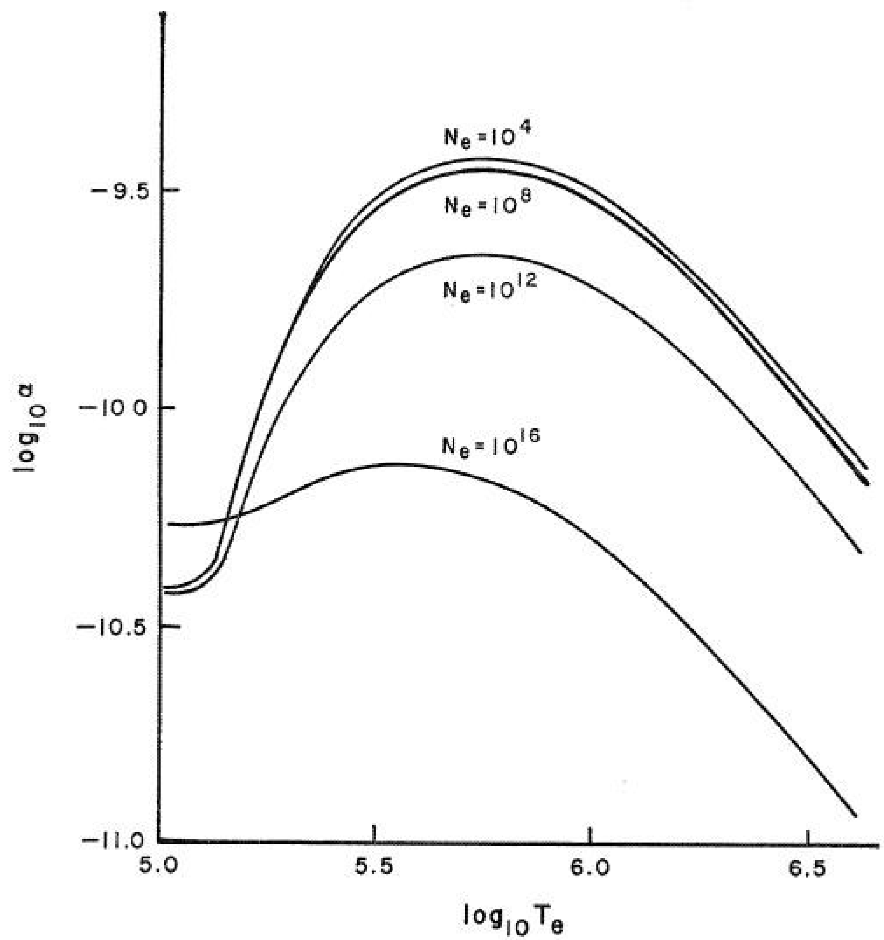


FIG. 7.—$Fe^{+8} + e$ recombination coefficient

Modelling Oxygen Ion Populations

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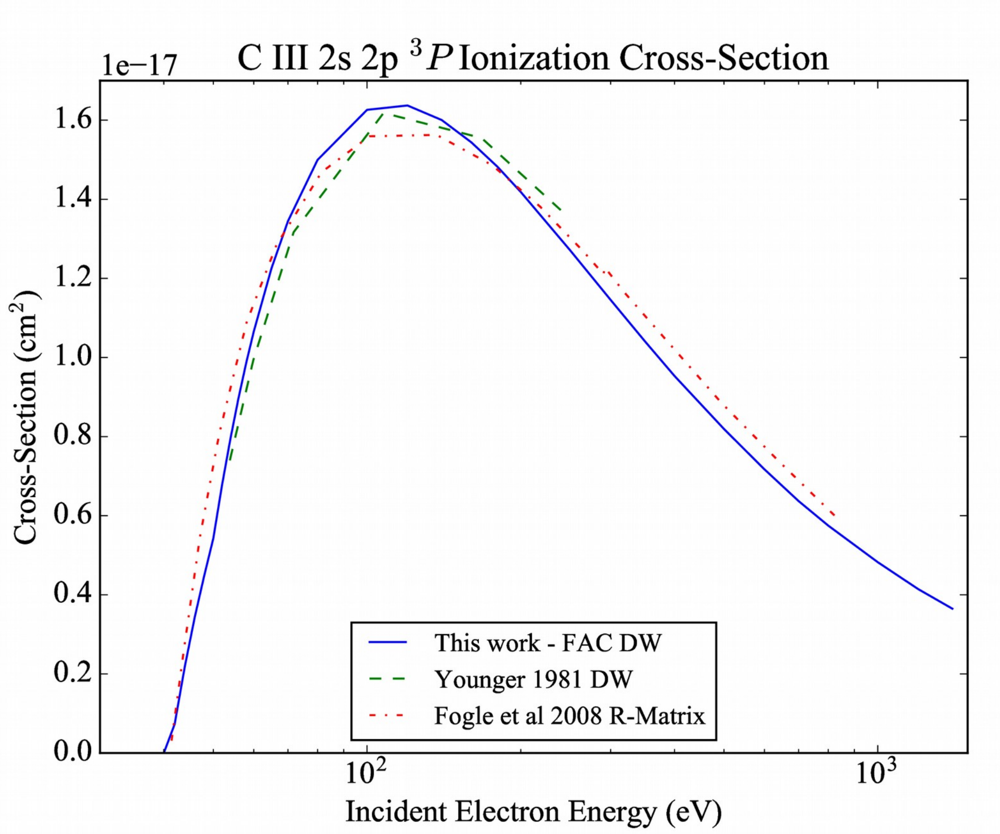
1) Background
2) Modelling
3) Results – adding density effects
4) Results - adding other atomic processes
5) Future work

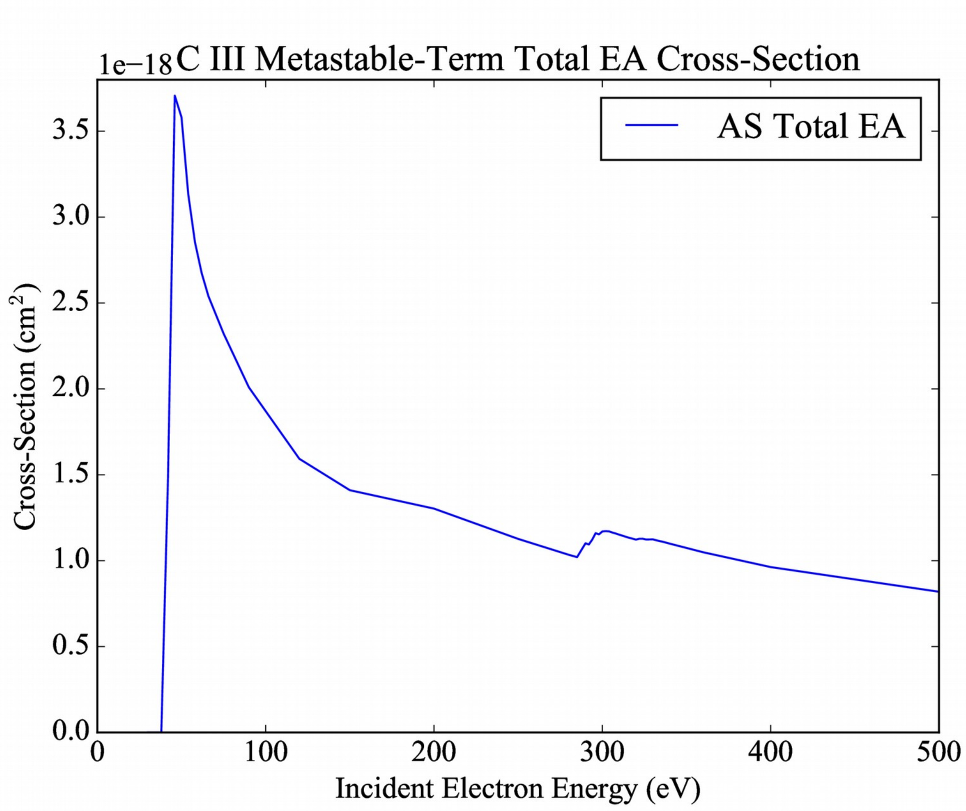
Results: Atomic Data

<u>Direct ionisation</u>



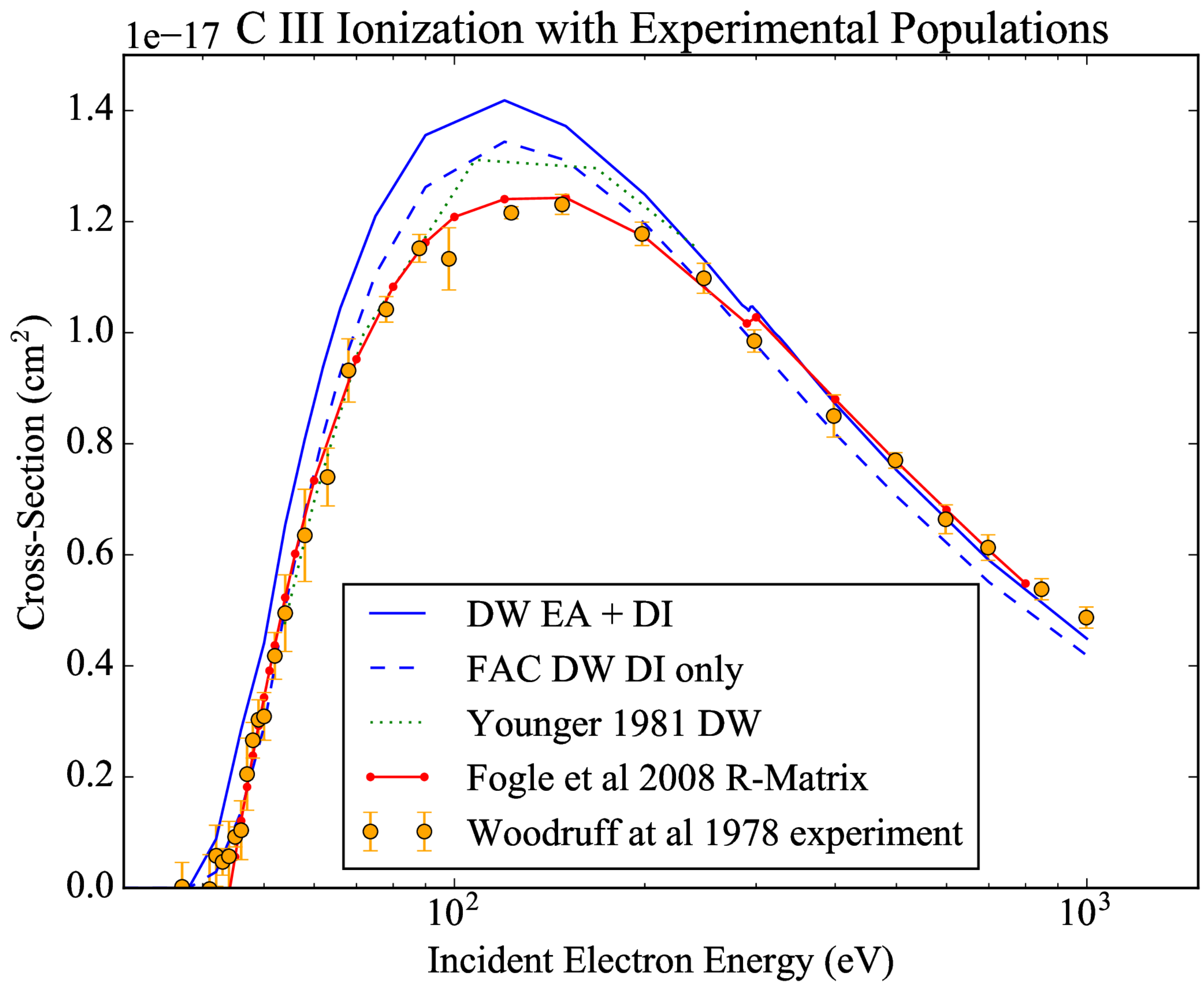
Using Flexible Atomic Code:
Gu M. F., 2008, Can. J. Phys., 86, 675

<u>Excitation - auto-ionisation</u>



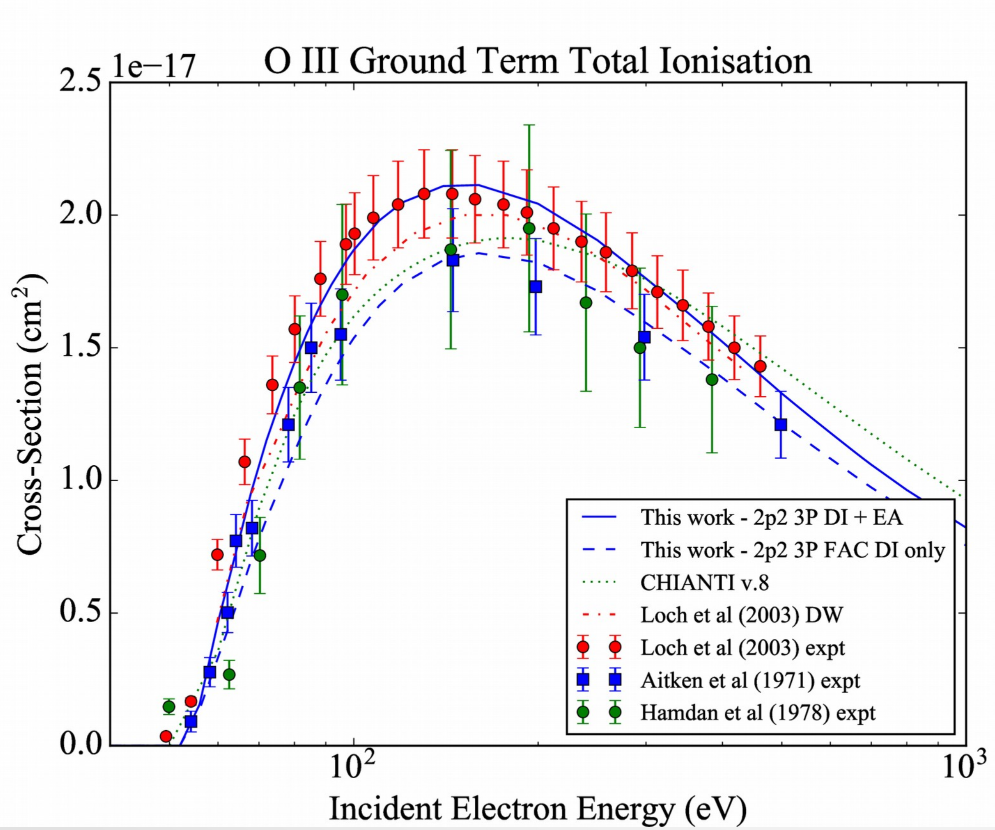
Using AUTOSTRUCTURE:
Badnell N. R., 2011, CPC, 182, 1528

Results: Atomic Data



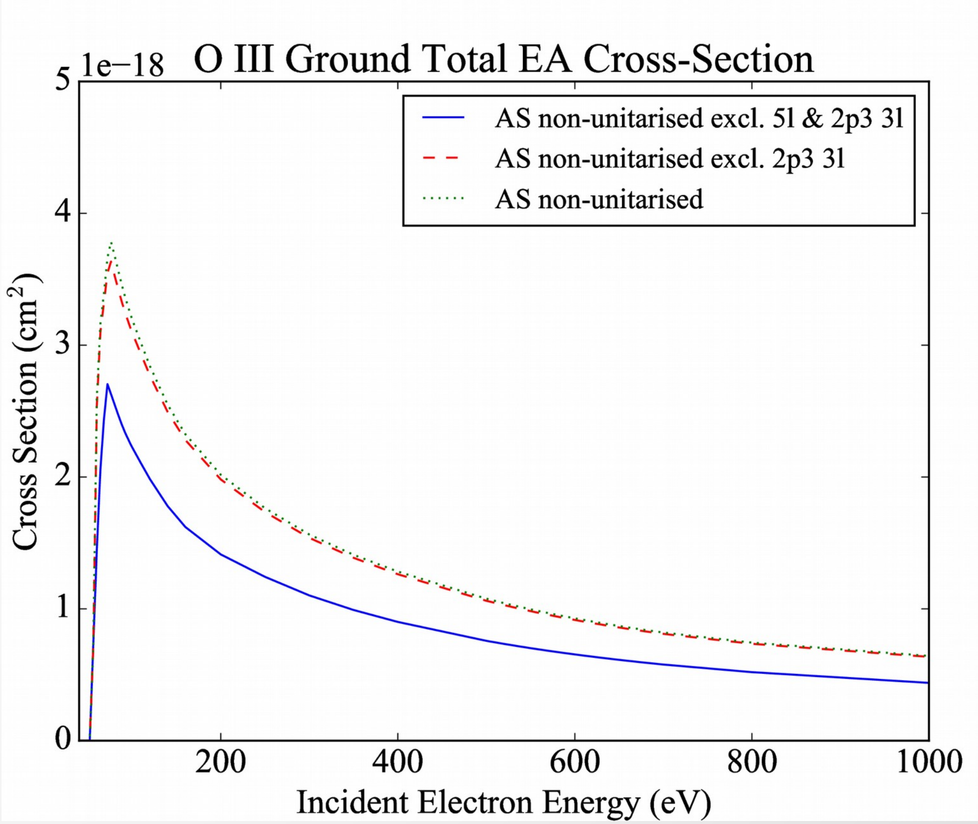
Results: Atomic Data

Direct ionisation



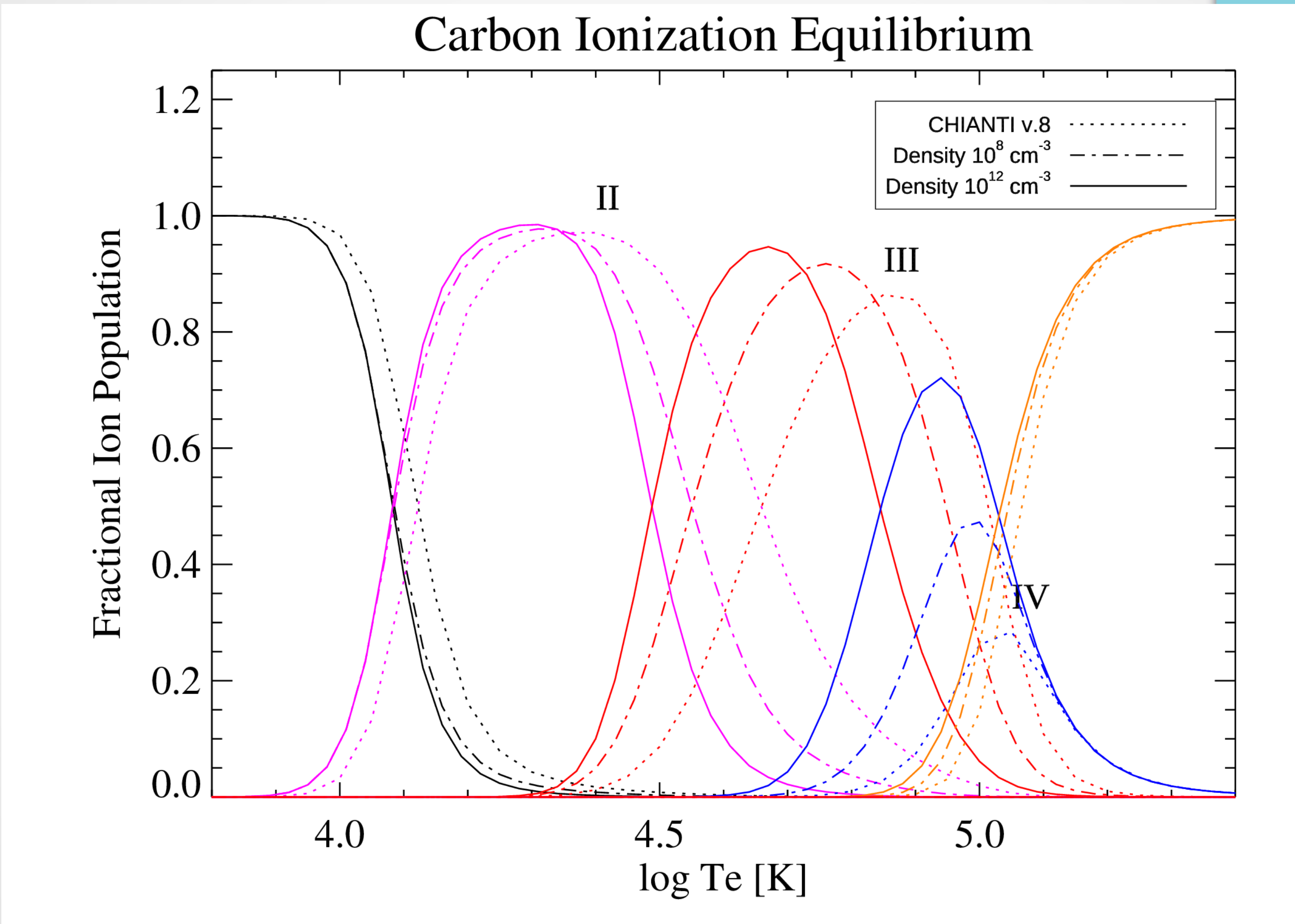
Using Flexible Atomic Code:
Gu M. F., 2008, Can. J. Phys., 86, 675

Excitation - auto-ionisation



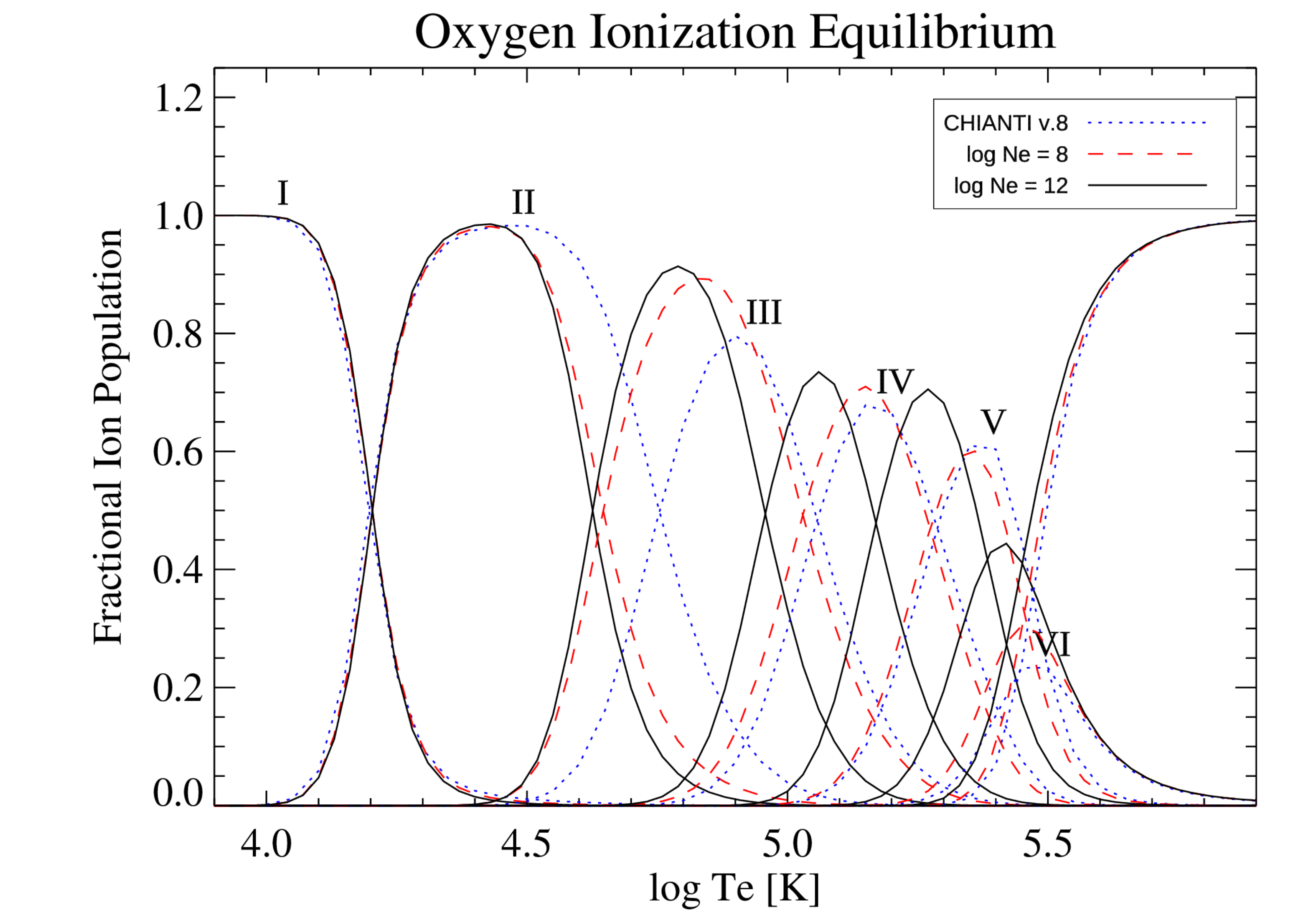
Using AUTOSTRUCTURE:
Badnell N. R., 2011, CPC, 182, 1528

Results: Ion Populations



Using CHIANTI for bound-bound transition data, DR Project for recombination data from Atomic Processes for Astrophysical Plasma website: www.apap-network.org

Results: Ion Populations



Using CHIANTI for bound-bound transition data, DR Project for recombination data from Atomic Processes for Astrophysical Plasma website: www.apap-network.org

Comparison with Observations

Intensity observed along line of sight:

$$I_{ij} = \frac{E_{ij}}{4\pi} \int A_{ij} N_j^z \, dh$$

Ratio of predicted to observed intensities

R_1 - Chianti coronal approximation ion populations
R_2 - Ion populations from this work for carbon and oxygen

At constant pressure 3×10^{14} cm^{-3} K (Avrett & Loeser 2008, ApJS, 175, 229)

Using quiet Sun observations of:
- Warren 2005, ApJS, 157, 147, (CDS & SUMER)
- Wilhelm et al. 1998, A&A, 334, 685 (SUMER)
- Brekke P., 1993, ApJS, 87, 443 (HRTS)

Ion	λ_{obs}	I_{obs}	T_1	T_2	R_1	R_2
C II	1334.53	937.0[a]	4.40	4.18	0.56	0.66
C II	1335.71	1350.0[a]	4.40	4.18	0.75	0.90
C II	1036.34	57.9[a]	4.48	4.34	0.92	0.81
C II	1037.00	70.1[a]	4.48	4.34	1.50	1.31
C II	903.99	10.0[a]	4.51	4.40	2.22	1.68
C II	904.46	6.3[a]	4.51	4.40	1.78	1.34
C II	903.59	9.2[a]	4.52	4.40	1.62	1.21
C II	904.14	23.1[a]	4.52	4.39	3.21	2.41
C III	977.04	702.0[c]	4.82	4.70	0.65	0.86
C III	1174.88	37.4[c]	4.82	4.72	0.65	0.83
C III	1175.74	104.0[c]	4.82	4.72	0.71	0.89
C IV	1548.24	212.0[b]	5.10	4.98	0.43	1.28
C IV	1550.82	134.0[b]	5.10	4.98	0.34	1.02

Ion	λ_{obs}	I_{obs}	$T_{eff}^{(1)}$	$T_{eff}^{(2)}$	$R^{(1)}$	$R^{(2)}$
O II	834.47	31.0	4.63	4.53	2.85	2.35
O II	832.76	12.9	4.63	4.53	2.28	1.88
O II	833.33	21.9	4.63	4.54	2.67	2.20
O II	718.50	14.6	4.69	4.62	2.86	1.66
O III	1660.79	19.3[a]	4.82	4.76	0.44	0.58
O III	835.29	78.6	4.88	4.82	1.01	1.13
O III	833.74	51.0	4.88	4.82	1.08	1.21
O III	835.10	11.7	4.89	4.82	1.20	1.34
O III	702.85	27.5	4.91	4.84	1.12	1.15
O III	703.85	43.5	4.92	4.85	1.12	1.16

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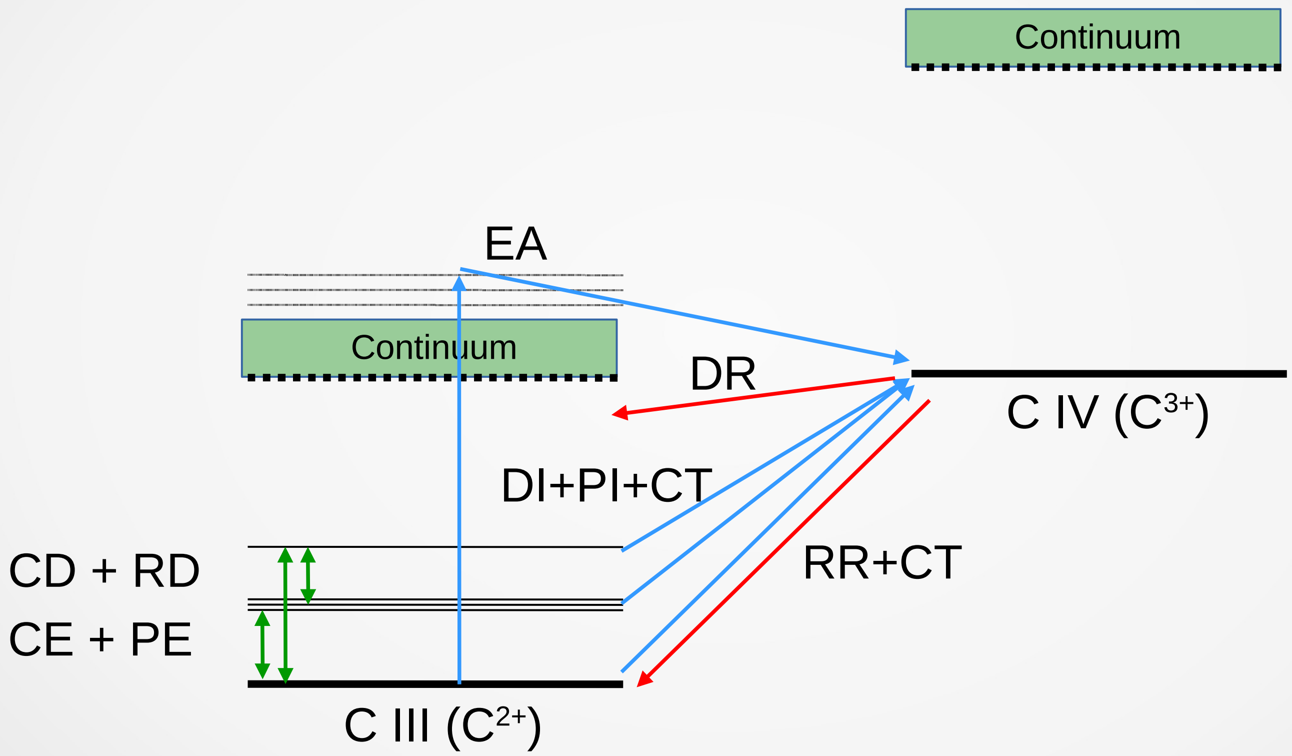
Modelling: Level Resolved



DI – Direct Ionisation PI – Photo-ionisation EA – Excitation-Autoionisation
RR/RD – Radiative Recombination/Decay DR – Dielectronic Recombination CT – Charge Transfer
CE/CD – Collisional Excitation/De-excitation PE – Photo-excitation

Methods: Modelling new atomic processes

Photo-ionisation

Demonstrated for carbon by Nussbaumer H. & Storey P. 1975, A&A, 44, 321

$$\alpha_{ij}^{PI} = 4\pi \int_{\nu_0}^{\infty} \frac{\sigma_{ij}(\nu)}{h\nu} J_\nu \, \mathrm{d}\nu$$

Cross sections from:
Badnell N. R., 2006, ApJS, 167, 334

Radiances from:
Whole Heliospheric Interval reference spectrum of
Woods T. N., et al., 2009, Geophys. Res. Lett., 36, L01101

Covers wavelength range 0.5-24000Å

Charge transfer

Demonstrated for silicon by Baliunas S., & Butler S., 1980, ApJ, 235, L45

Reactions of type:

$A^{+z} + H \leftrightarrow A^{+(z-1)} + H^{+}$

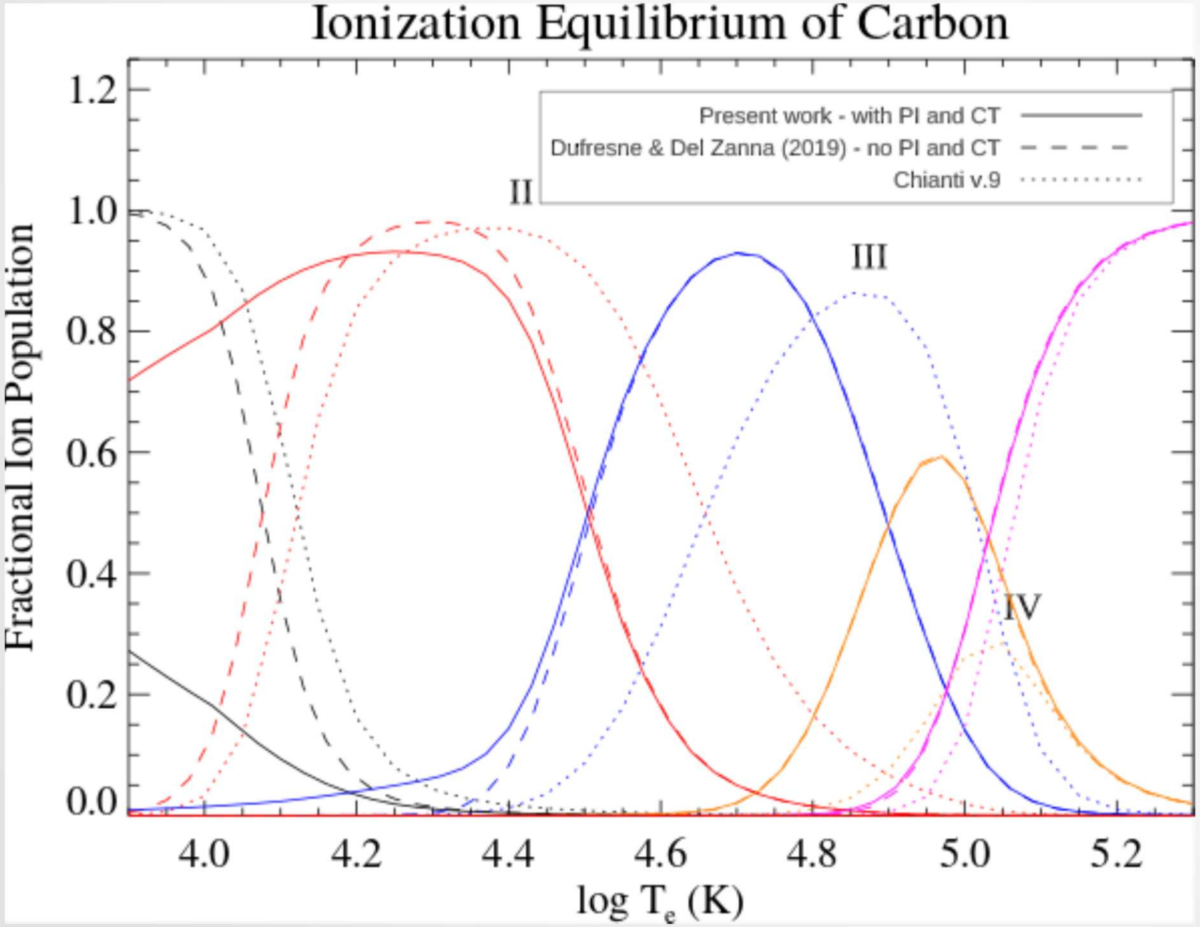
$$R_{\mathrm{CT}}(T_e) = \frac{N_{\mathrm{H\,I}}}{N_{\mathrm{H}}} \frac{N_{\mathrm{H}}}{N_e} N_e \, \alpha_{\mathrm{CT}}(T_e)$$

Hydrogen fractional populations and abundance of hydrogen relative to free electrons taken from:

Avrett E. H., Loeser R., 2008, ApJS, 175, 229

Results: Ion Populations

With all atomic processes combined



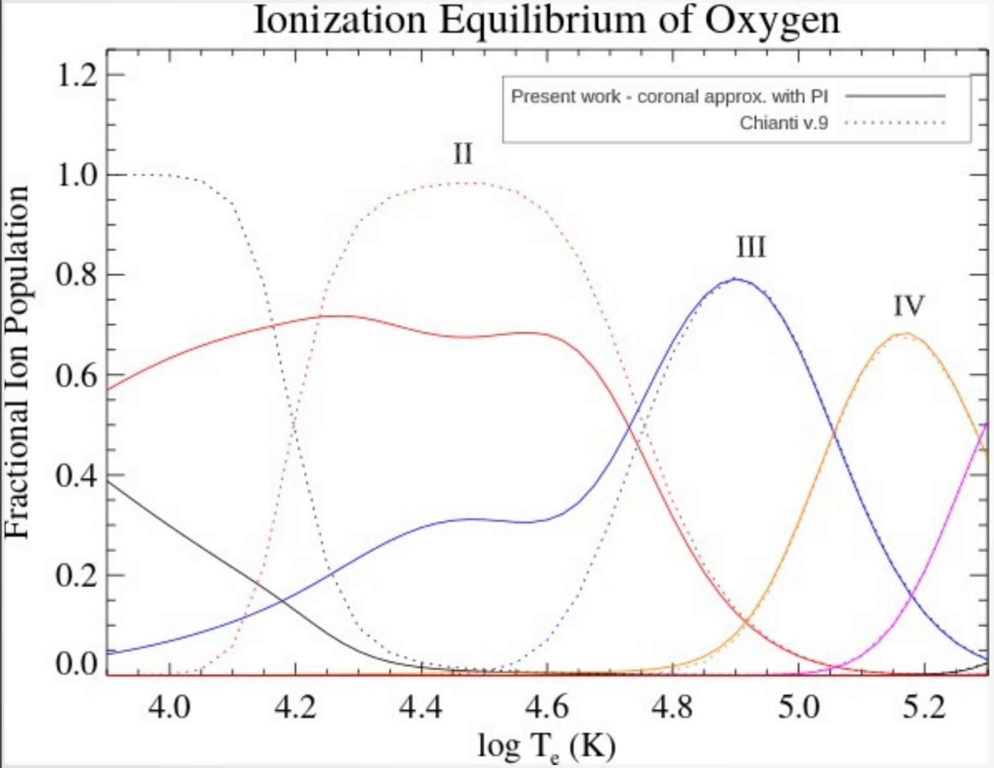
Comparison with observations

Ion	λ_{obs}	I_{obs}	R_c	R_e	R_f
C II	1334.53	937[a]	0.56	0.66	0.94
C II	1335.71	1350[a]	0.75	0.90	1.29
C II	1036.34	57.9[a]	0.92	0.81	0.69
C II	1037.00	70.1[a]	1.50	1.31	1.12
C II	903.99	9.98[a]	2.22	1.68	1.29
C II	904.46	6.29[a]	1.78	1.34	1.03
C II	903.59	9.19[a]	1.62	1.21	0.94
C II	904.14	23.1[a]	3.21	2.41	1.87
C II	1323.91	1.72[b]	2.47	1.30	0.98
C III	977.04	702[c]	0.65	0.86	0.87
C III	1174.88	37.4[c]	0.65	0.83	0.83
C III	1175.74	104[c]	0.71	0.89	0.89
C III	1176.37	36.2[c]	0.67	0.85	0.85
C IV	1548.24	212[b]	0.43	1.28	1.26
C IV	1550.82	134[b]	0.34	1.02	1.00

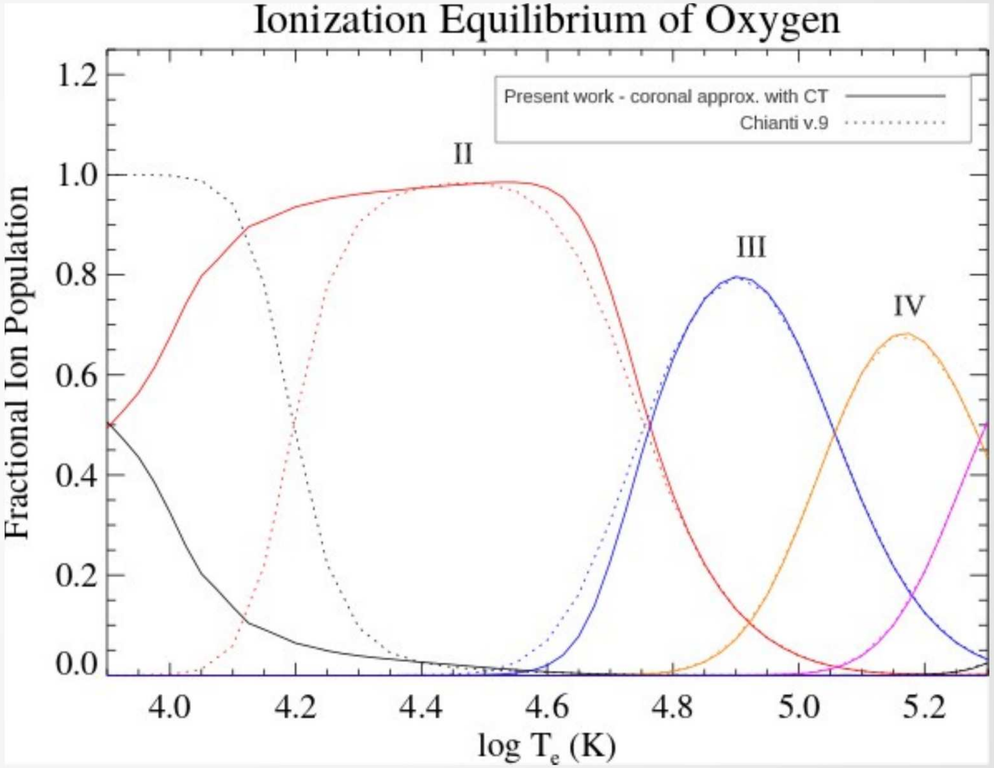
R_c – coronal approximation
R_e – density effects added
R_f – all processes added

Results: Ion Populations

With photo-ionisation only



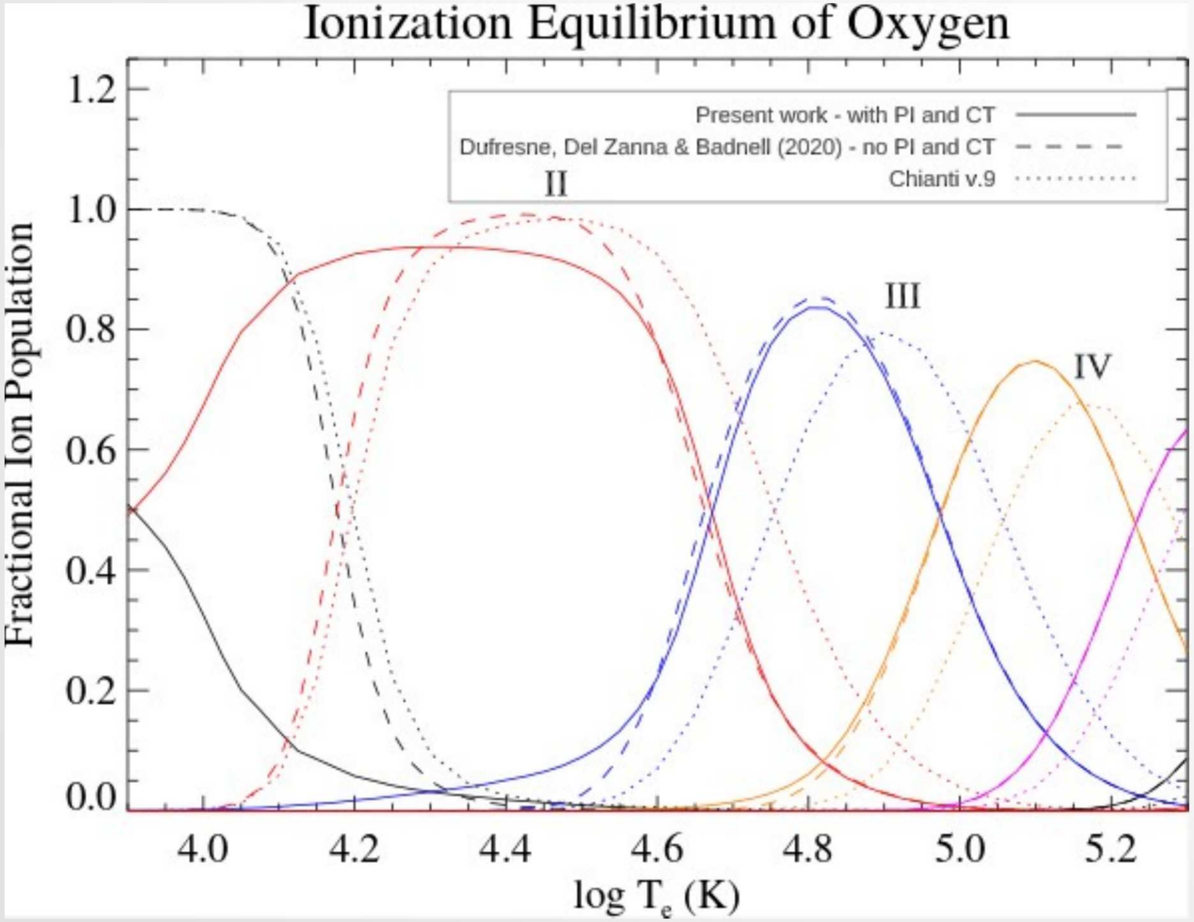
With charge transfer only



Charge transfer data:
Stancil P. C., et al. 1999A, J. Phys. B, 32, 1523
Barragán P., et al. 2006, ApJ, 636, 544
Wang J. G., et al. 2003, Phys. Rev. A, 67, 012710
Wu Y., et al. 2009, Phys. Rev. A, 79, 062711

Results: Ion Populations

With all atomic processes combined



Comparison with observations

Ion	λ_{obs}	I_{obs}	R_c	R_e	R_f
O II	832.75	11.2[a]	3.02	2.66	2.20
O II	834.45	35.5[a]	2.85	2.51	2.08
O II	833.32	24.5[a]	2.75	2.42	2.01
O II	718.49	15[a]	2.10	1.39	1.22
O II	796.66	2.84[d]	1.71	1.32	1.21
O III	1660.80	19.3[b]	0.44	0.61	0.79
O III	832.92	13.7[c]	1.21	1.32	1.37
O III	833.74	47.3[c]	1.06	1.14	1.19
O III	835.10	12.9[c]	0.98	1.06	1.10
O III	835.26	63.8[c]	1.09	1.19	1.23
O III	702.89	27.5[a]	1.16	1.15	1.17

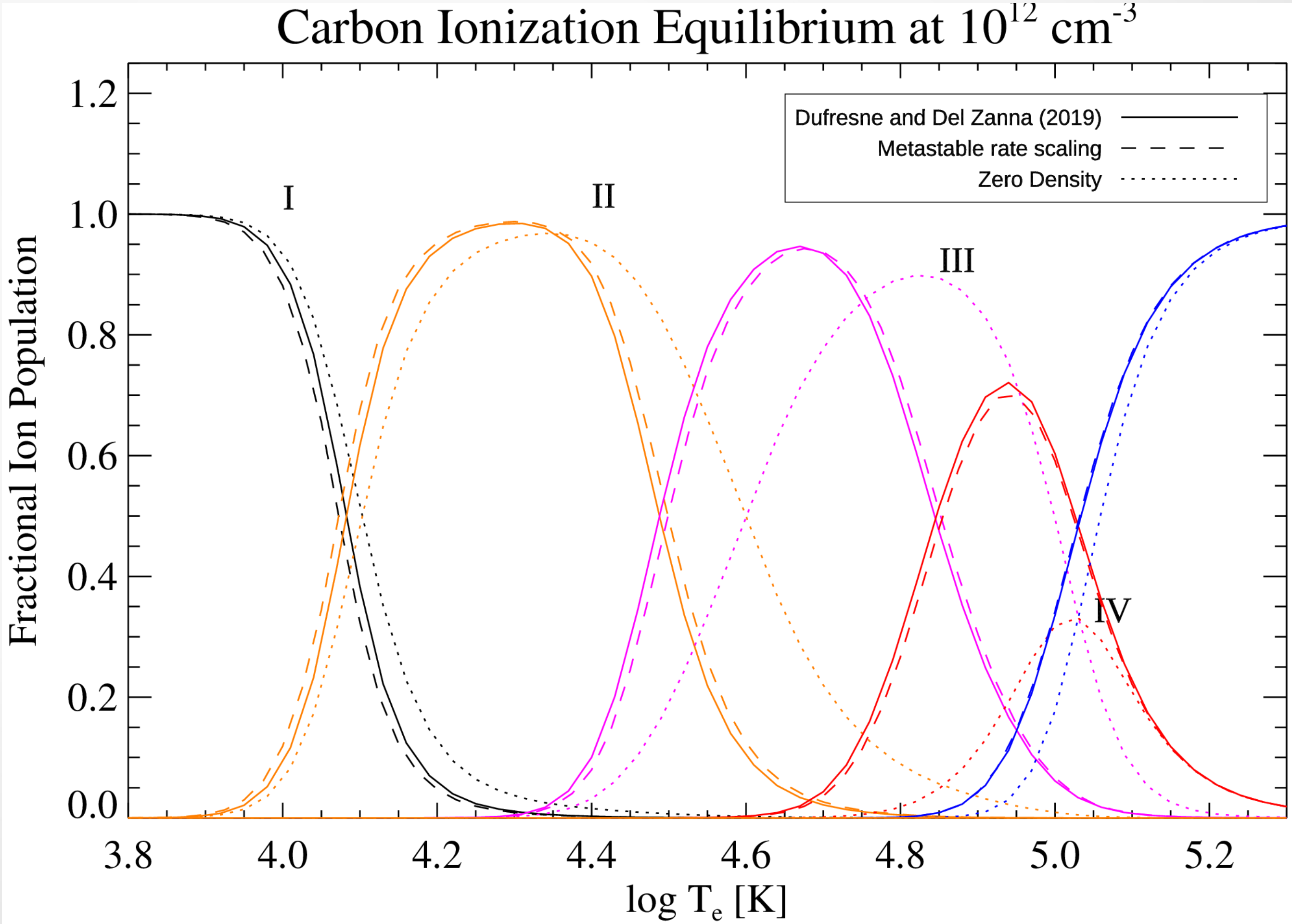
R_c – coronal approximation

R_e – density effects added

R_f – all processes added

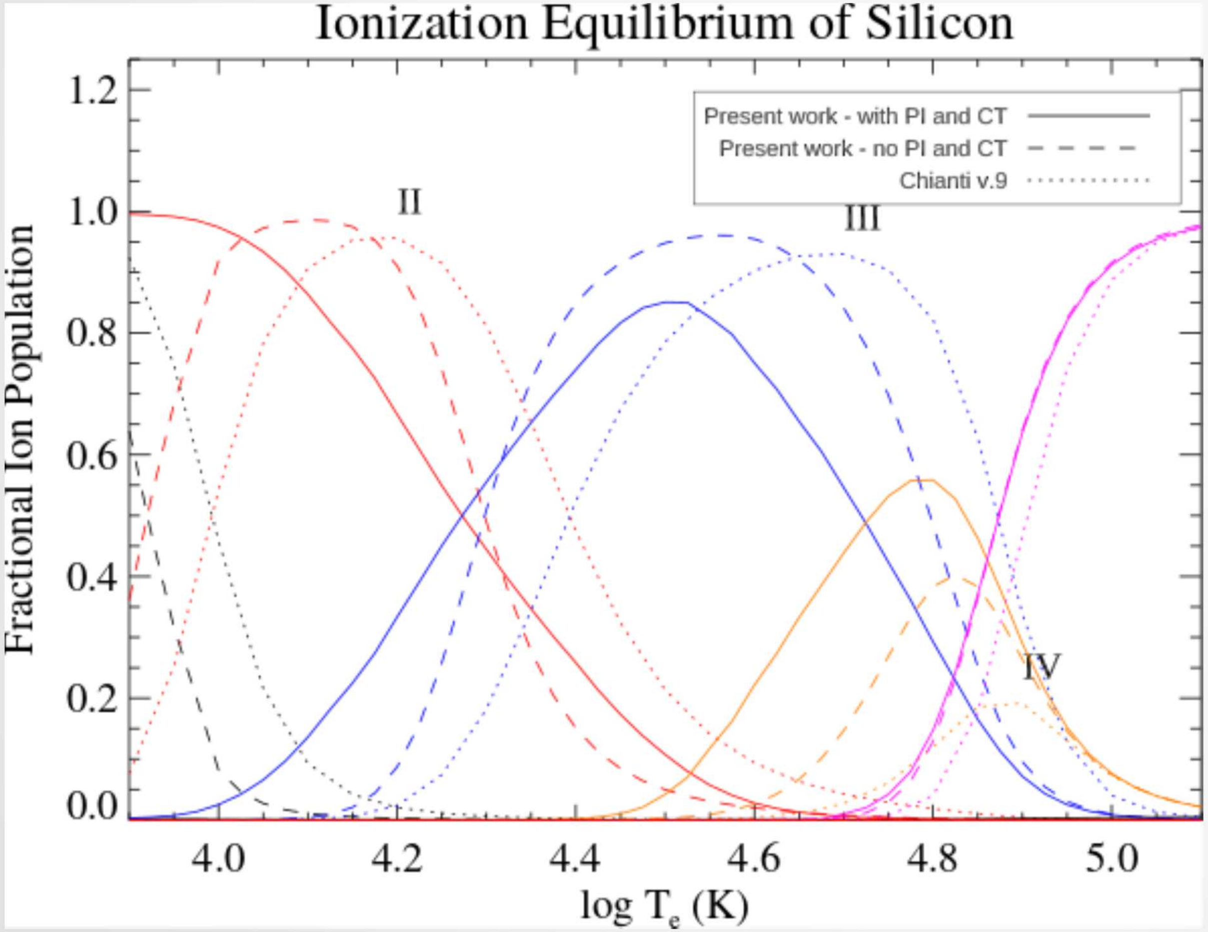
Results: Ion Populations

<u>Ionisation for other elements</u>:
Ground level - Dere K. P., 2007, A&A, 466, 771
Metastable level – enhanced Dere rate coefficients by ratio of metastable to ground rate coefficients of Burgess A., Chidichimo M. C., 1983, MNRAS, 203, 1269



Results: Ion Populations

With all atomic processes combined



Comparison with observations

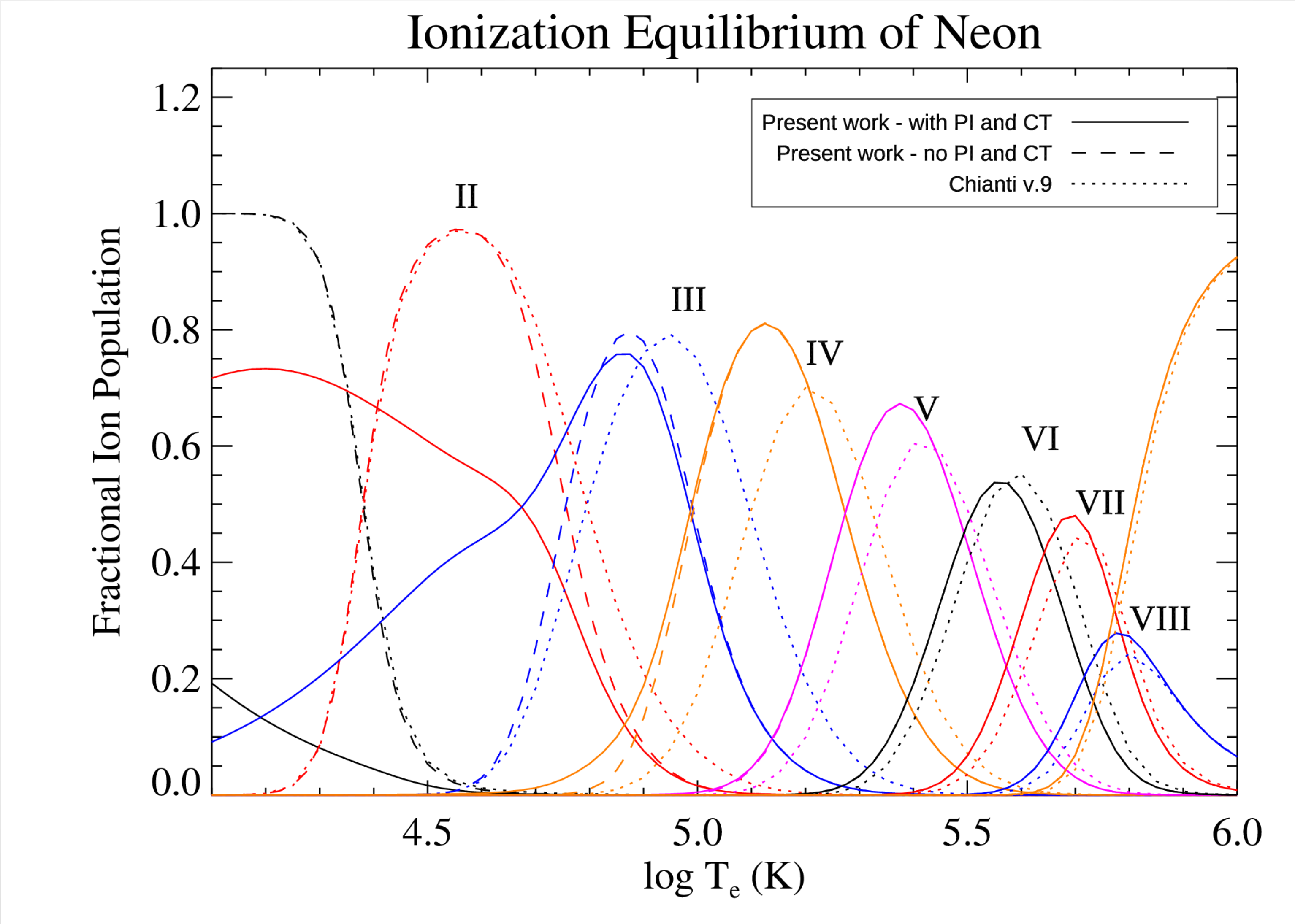
Ion	λ_{obs}	I_{obs}	R_c	R_e	R_f
Si II	1304.38	38.8^b	0.41	0.49	0.77
Si II	1309.32	69.7^b	0.40	0.47	0.74
Si II	1260.42	42.9^b	1.26	1.38	1.91
Si II	1264.75	123^b	0.78	0.86	1.18
Si II	1265.01	34.1^b	0.29	0.32	0.45
Si II	1193.31	10.7^d	2.55	2.62	3.26
Si II	1197.41	8.59^d	1.65	1.69	2.10
Si II	1190.43	14.2^d	0.92	0.94	1.15
Si II	1194.49	23^d	2.97	3.04	3.72
Si III	1892.03	832^h	0.47	0.85	1.08
Si III	1206.51	630^e	0.69	0.87	0.69
Si III	1294.54	4.9^e	0.84	0.84	0.60
Si III	1298.89	16.9^e	0.83	0.83	0.59
Si III	1296.73	3.8^e	0.83	0.84	0.60
Si III	1108.37	4.3^e	0.61	0.57	0.40
Si III	1109.97	6.5^e	1.00	0.92	0.66
Si III	1113.23	15.5^e	1.07	0.97	0.70
Si IV	1393.78	280^a	0.06	0.16	0.33
Si IV	1402.77	127^a	0.07	0.18	0.37

R_c – coronal approximation
R_e – density effects added
R_f – all processes added

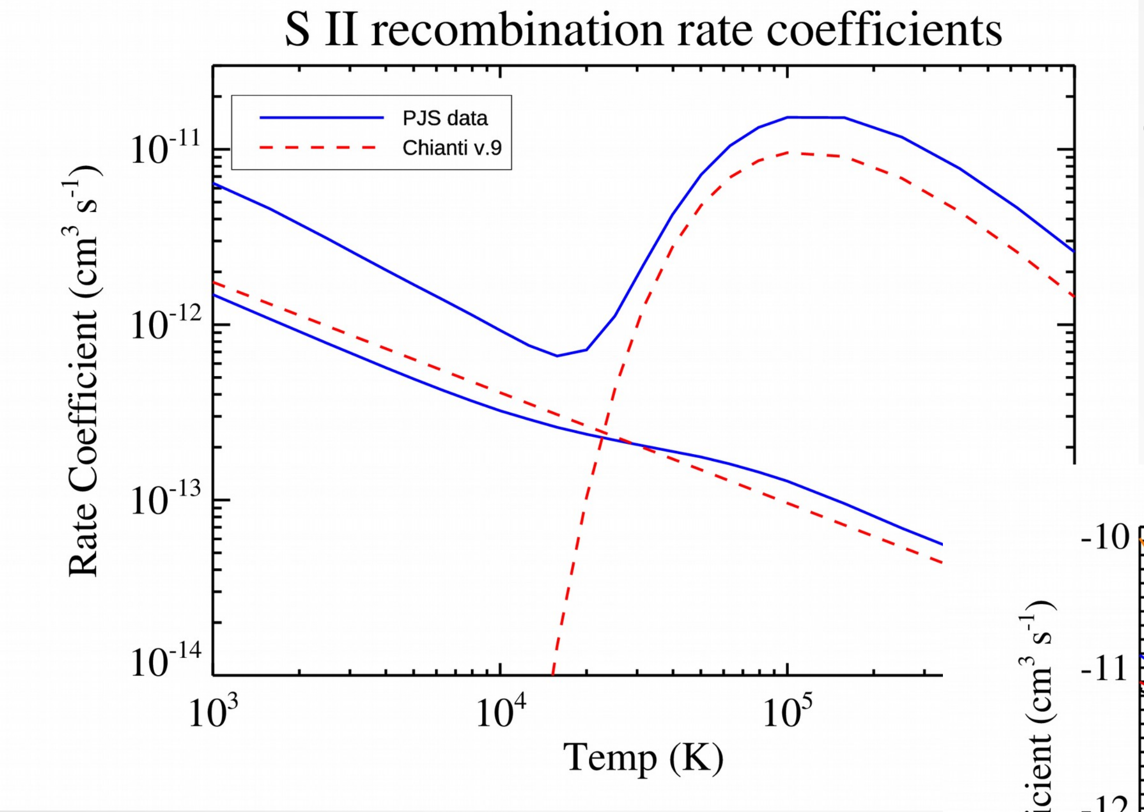
Kimura M., et al. 1996, ApJ, 473, 1114   Clarke N., et al. 1999 J.Phys., 31, 533
Wang J. G., et al. 2006, Phys. Rev. A, 74, 052709
Stancil P. C., et al. 1999, J. Phys. B, 32, 1523

Results: Ion Populations

With all atomic processes combined

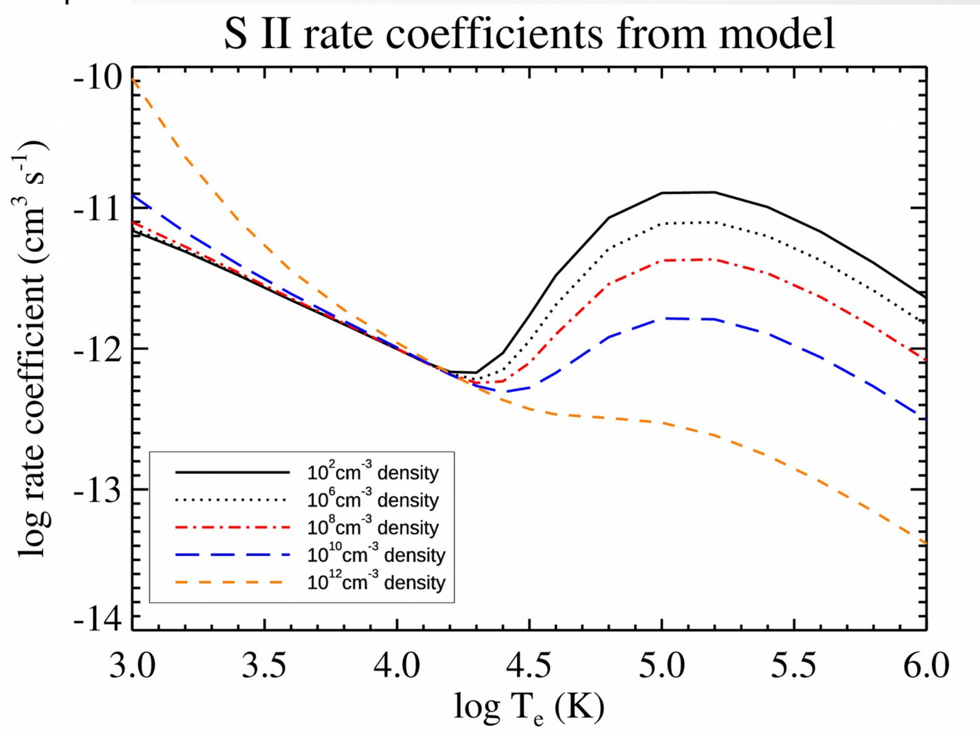


Results: New recombination calculation for S II



Comparison of new recombination rates from Pete Storey with Chianti

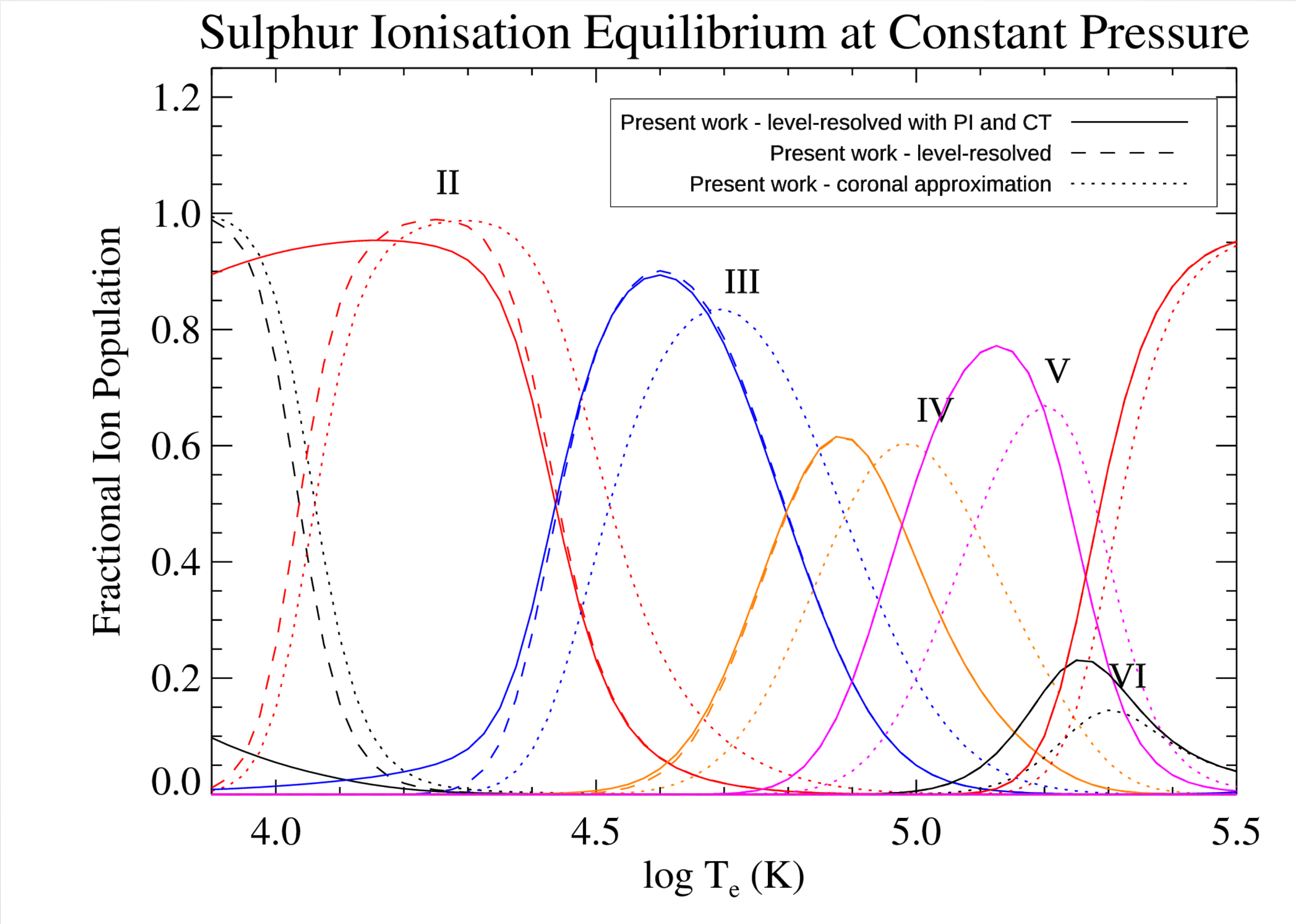
Existing CHIANTI data:
RR- Mazzitelli, G., Mattioli, M., 2002, ADNDT, 82, 313
DR - Mazzotta, P., et al. 1998, A&ASS, 133, 403



Suppression of effective recombination rates with density

Results: Ion Populations

<u>With all atomic processes combined</u>



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1) Background
2) Modelling
3) Results – adding density effects
4) Results - adding other processes
5) Future work

Modelling Ion Populations

Summary

1) Calculated level-resolved direct and indirect ionization rates
2) Metastable levels included in modelling
3) Simulated dielectronic recombination suppression in modelling
4) Added photo-induced and charge transfer processes
5) Improved predicted line intensities compared to observations

Future work

1) Level resolved modelling up to n~700
2) Simplified optical depth effects
3) Non-Maxwellian electrons
4) Time dependent ionisation