Generalised collisional-radiative modelling, contribution functions and solar spectra

Alessandra Giunta

Introduction

- Formation of He lines in the EUV solar spectrum enables understanding of the physics of the solar upper atmosphere (transition region and corona) plasma
- Observed intensities of He resonance lines are enhanced compared to theoretical models of the solar TR built up from other characteristic lines
- To what extent can emission measure distribution reproduce the observed fluxes of the He I and He II lines?
- He I (591.4 Å) intercombination line can be used as support to investigate the anomalous behaviour of He line intensities without including opacity effects
- New joint observations for all He I and He II EUV lines, using Hinode/EIS, SoHO/SUMER and SoHO/CDS
- Revisit of atomic data to build up updated contribution functions

Solar context

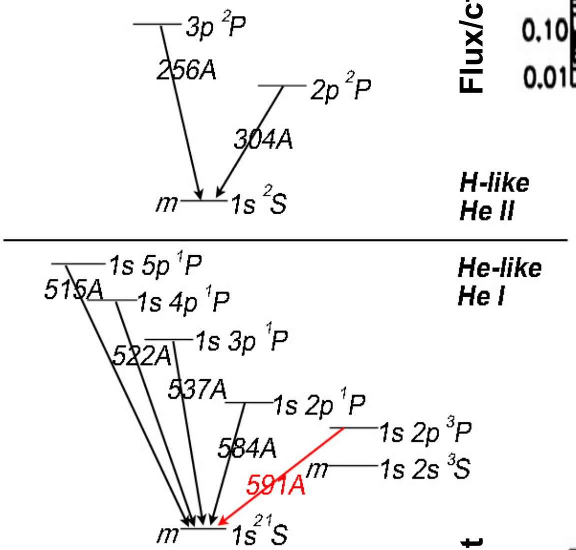
Problem of He enhancement

- Enhancement factors of 15 for He I 584.3 *Å* and 5.5 for He II 303.8 *Å* (*Jordan (1975)* : emission measure (EM) analysis)
- New enhancement factors of 2-5 for He I 584.3 *Å* and 2-9 for He II 303.8 *Å* (*Pietarila & Judge (2004)* : EM analysis and radiative transfer calculations)

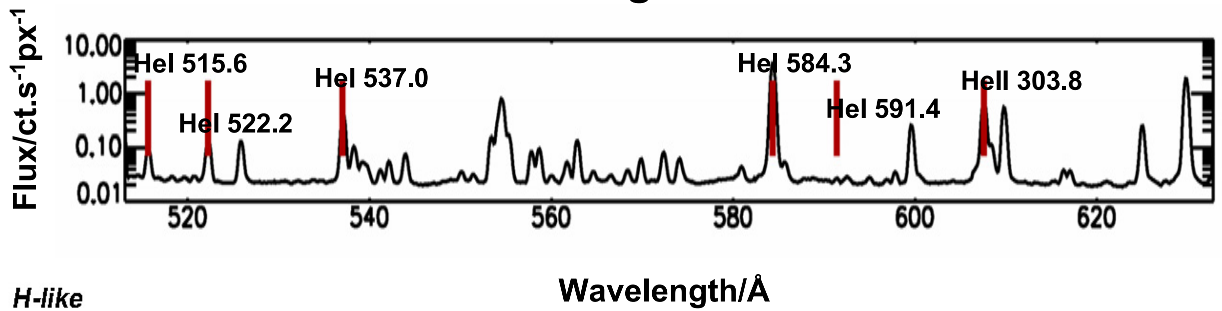
Analysis of quiet Sun and active regions

- *Jordan (1975)* : mixing low temperature He atoms and ions with higher temperature electrons
- *Shine et al. (1975)*, *Fontenla et al. (1993)*: diffusion effects
- *Andretta et al. (2000):* velocity redistribution
- *Smith & Jordan (2002)*: transport of He atoms and ions by turbulent motions
- *Mauas et al.(2005)*: He line formation in a specific active region prior to a two ribbon flare
- *Andretta et al. (2008)*: He line formation during the flare

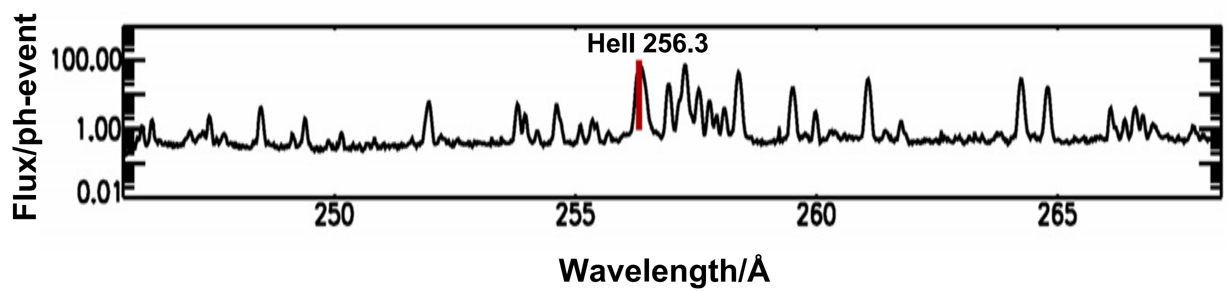
The observational spectroscopic dimension



Quiet Sun average for SoHO/CDS/NIS2



Quiet Sun average for Hinode/EIS



Requirements to clarify the He problem

Differential Emission Measure (D.E.M.) analysis

The D.E.M. describes the temperature and density structure of the solar atmosphere

Intensity of spectral line of optically thin plasma:

$$I_{j\to k} = \frac{A(Z)}{4\pi} \int G_{j\to k}(T_e)\,\Phi(T_e)\,dT_e$$

A realistic study of EUV He lines through D.E.M. analysis requires:

- **Measurements in EUV range** $\Longrightarrow$ $I_{j\to k}$
  (SoHO/SUMER, SoHO/CDS and Hinode/EIS)

- **Sophisticated atomic modelling** $\Longrightarrow$

$$\begin{cases} G_{j\to k}(T_e) = A_{j\to k} \dfrac{n_H}{n_e} \displaystyle\sum_{\rho=1}^{M_Z} F_{j\rho}^{(exc)} \dfrac{n_\rho}{n_{TOT}} \\ \Phi(T_e)\,dT_e \propto n_e^2\ dV \end{cases}$$

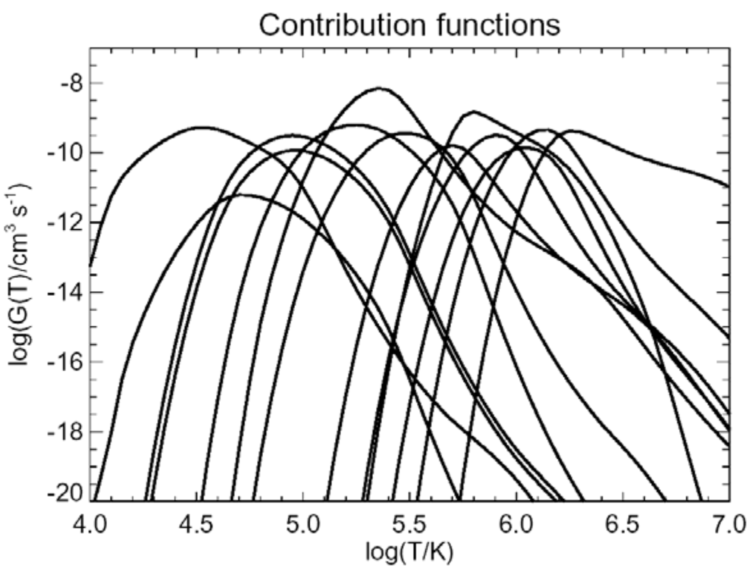
Initial approach - modelling

ADAS601: D.E.M. estimated by *data adaptive smoothing approach* (Lanzafame et al., 2005), using the integral inversion algorithm of Thompson (1990, 1991)

Input data

- Set of observed intensities I_i
- Elemental abundances $A(Z)$
- Contribution functions $G_i(T)$

$$I_i = \frac{A(Z)}{4\pi} \int_{T_1}^{T_2} G_i(T)\, \Phi(T)\, dT$$



Data for the lines included in D.E.M.

- Ionisation balance calculations of Arnaud & Rothenflug (1985) and Van Maanen (JET, 1985)

Data to reconstruct He line intensities

- Ionisation balance calculations of Summers et al. (2006) (Generalised Collisional-Radiative approach)

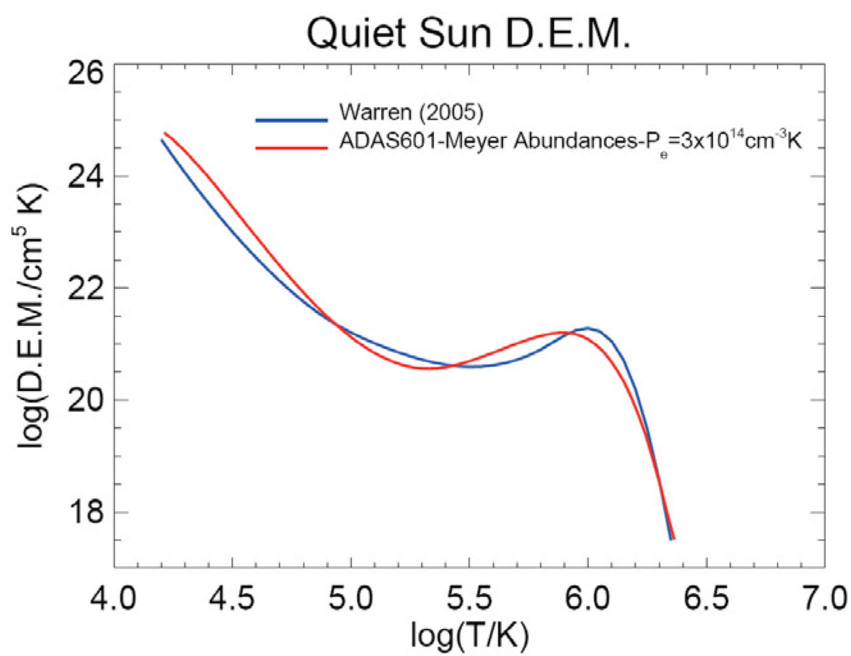
- New calculations for the distribution of level population for He I, merging R-matrix (Ballance, 2003; Paton, 2003) with Cowan code calculations to add n=5 levels

Initial approach - results

ABUNDANCE	$\frac{I_{OBS}(\mathrm{HeI}\ 5914\ \AA)}{I_{REC}(\mathrm{HeI}\ 5914\ \AA)}$
Gr.&And. (1989)	2.01
Meyer (1985)	1.67
Fl.&Sch. (1999)	4.51
Feldman (2000)	4.16

- Ratio between observed and reconstructed intensity for the intercombination line at electron pressure $P_e=3\times10^{14}cm^{-3}K$, using four sets of abundances: photospheric from Grevesse & Anders (1989), coronal from Meyer (1985), Fludra & Schmelz (1999) and Feldman et al. (2000)

- Comparison between D.E.M. for quiet Sun using Meyer abundance at $P_e=3\times10^{14}cm^{-3}K$ with the Warren (2005) emission measure distribution



New joint observations

- **Campaign of April 2009:**

  1. 17th April 2009 12:00-16:00 UT, Sun centre pointing
  2. 28th April 2009 20:00-24:00 UT, Sun centre pointing

- **Instruments:**

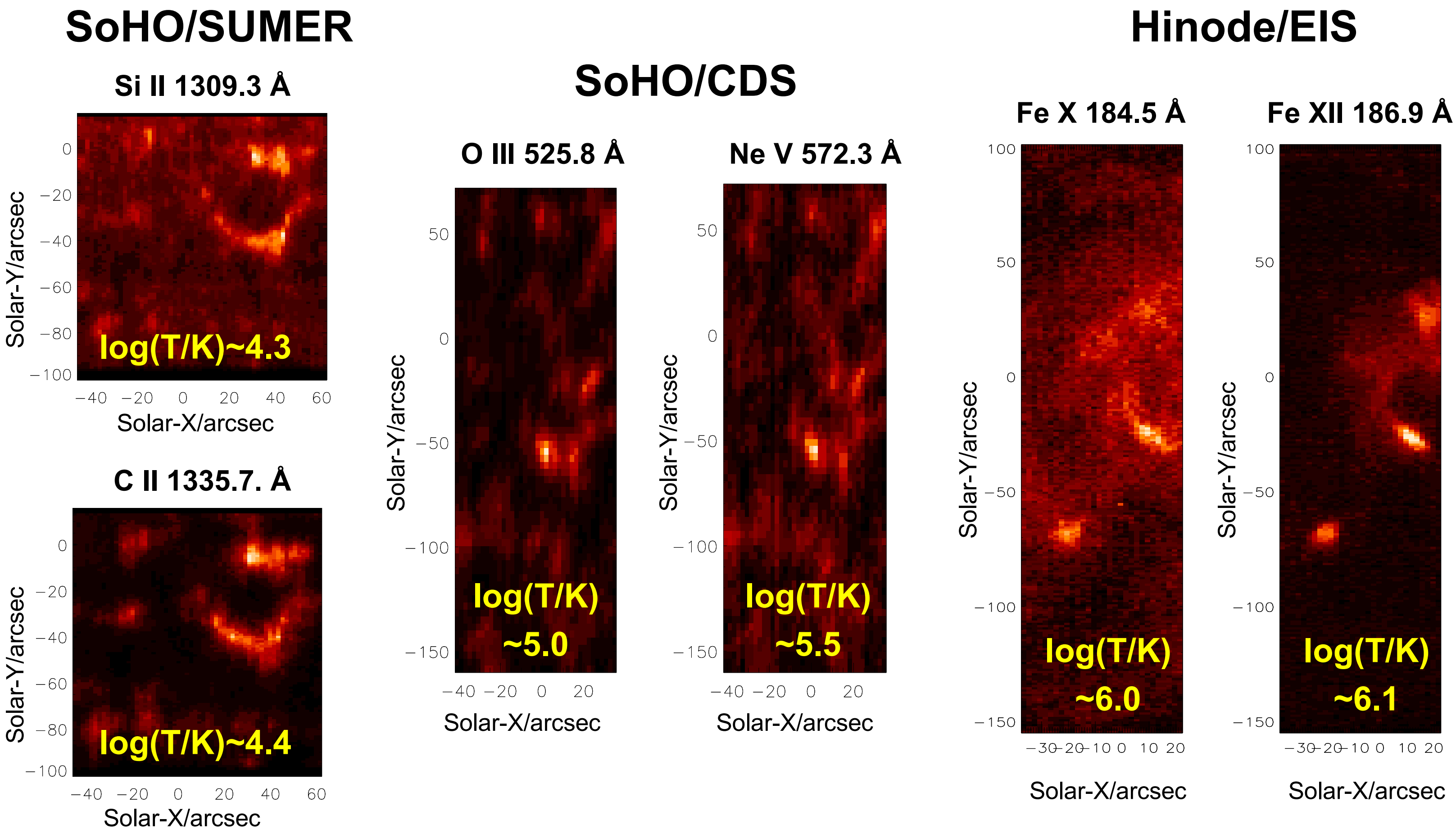
  Solar UV Measurements of Emitted Radiation onboard SoHO
  Coronal Diagnostic Spectrometer onboard SoHO
  EUV Imaging Spectrometer onboard Hinode (Solar-B)

- **New observation sequences:**

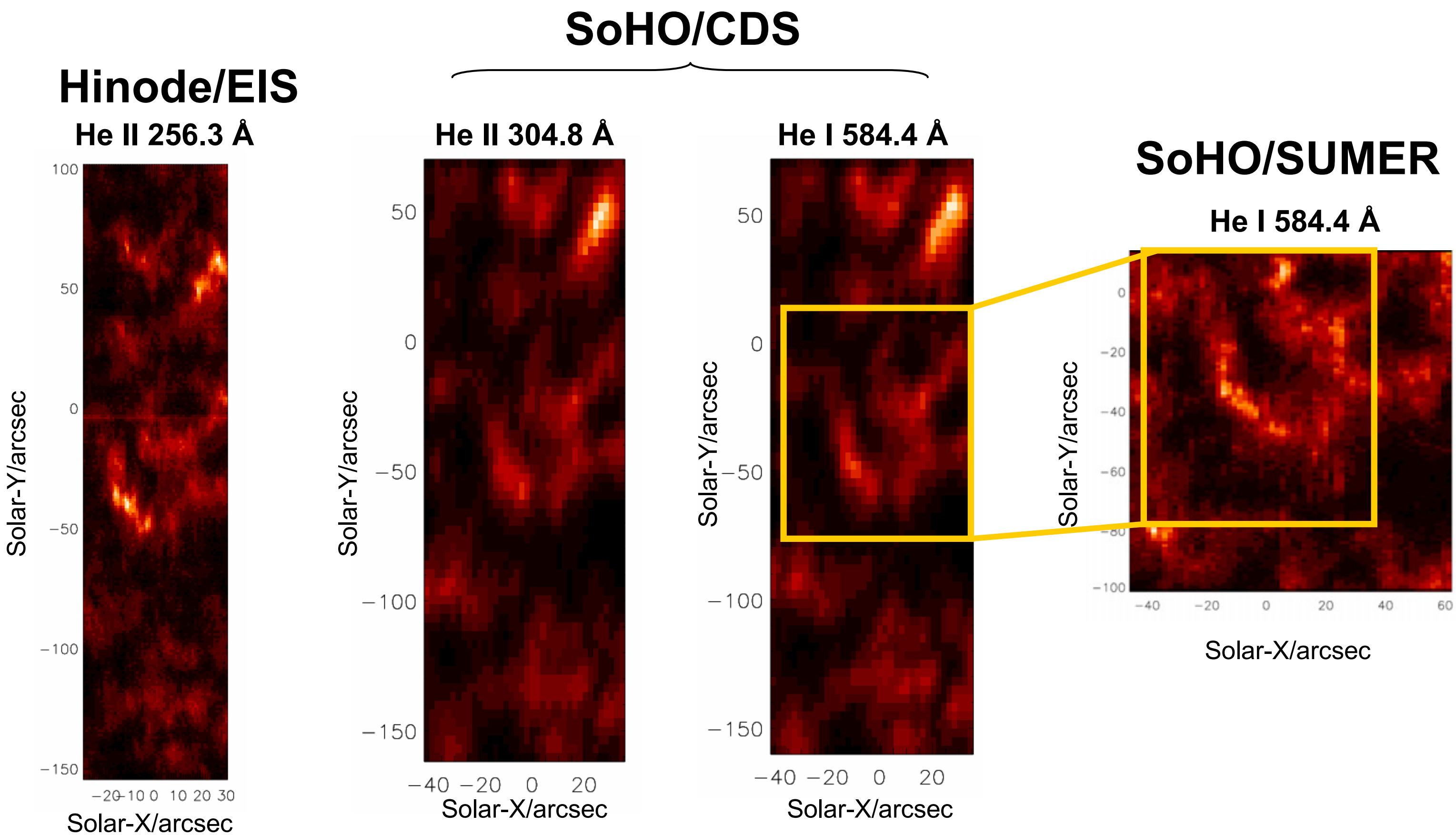
  - Helium lines: He I, He II
  - Lines at log(T/K)≤4.5: e.g. Si II, C II
  - Lines at 4.5≤log(T/K)≤6.0: e.g. O III, Ne V
  - Lines at log(T/K)≥6.0: e.g. Fe X, Fe XII
  - Lines for co-alignment: e.g. O IV, O V, Si VII

- **Calibration and co-alignment**

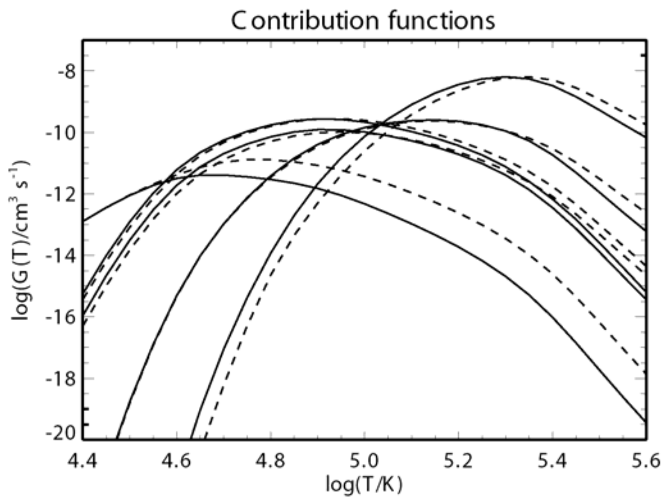
Images showing temperature variability



Example of He images



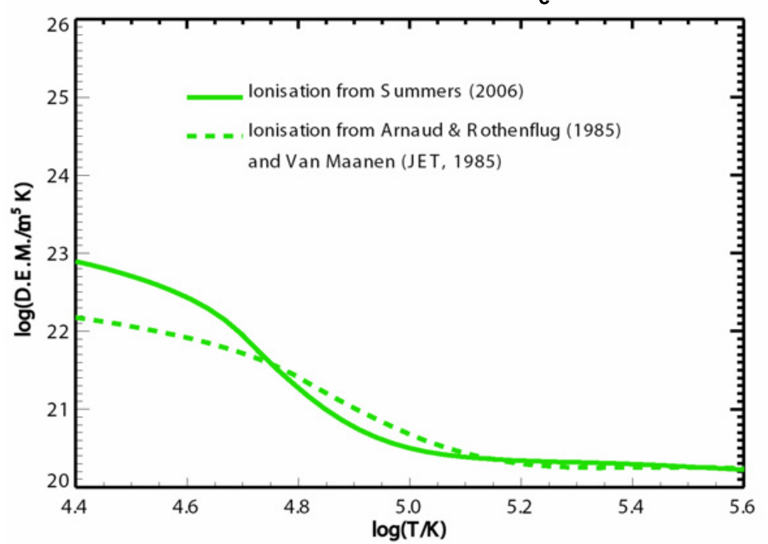
Update of contribution functions



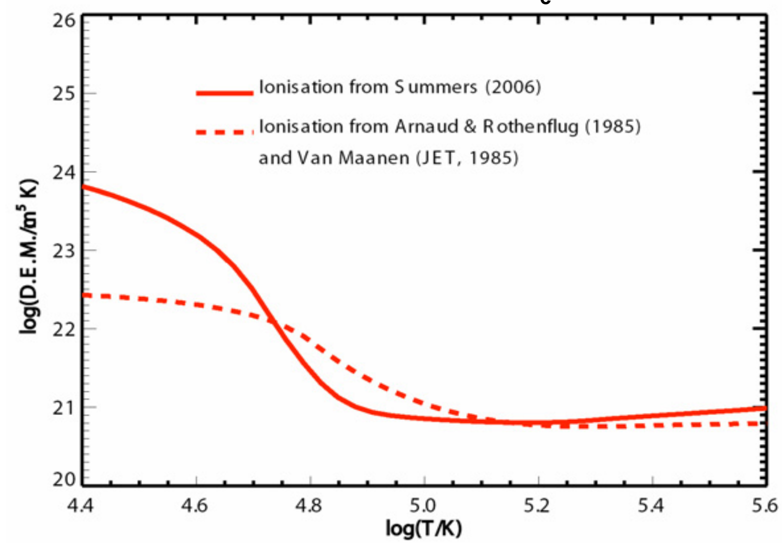
Solid line: G(T) and D.E.M. using ionisation balance of Summers et al. (2006)

Dashed line: G(T) and D.E.M. using ionisation balance of Arnaud & Rothenflug and Van Maanen (1985)

QS D.E.M. - Feldman Ab. - $P_e=10^{16}cm^{-3}K$



AR D.E.M. - Feldman Ab. - $P_e=10^{16}cm^{-3}K$

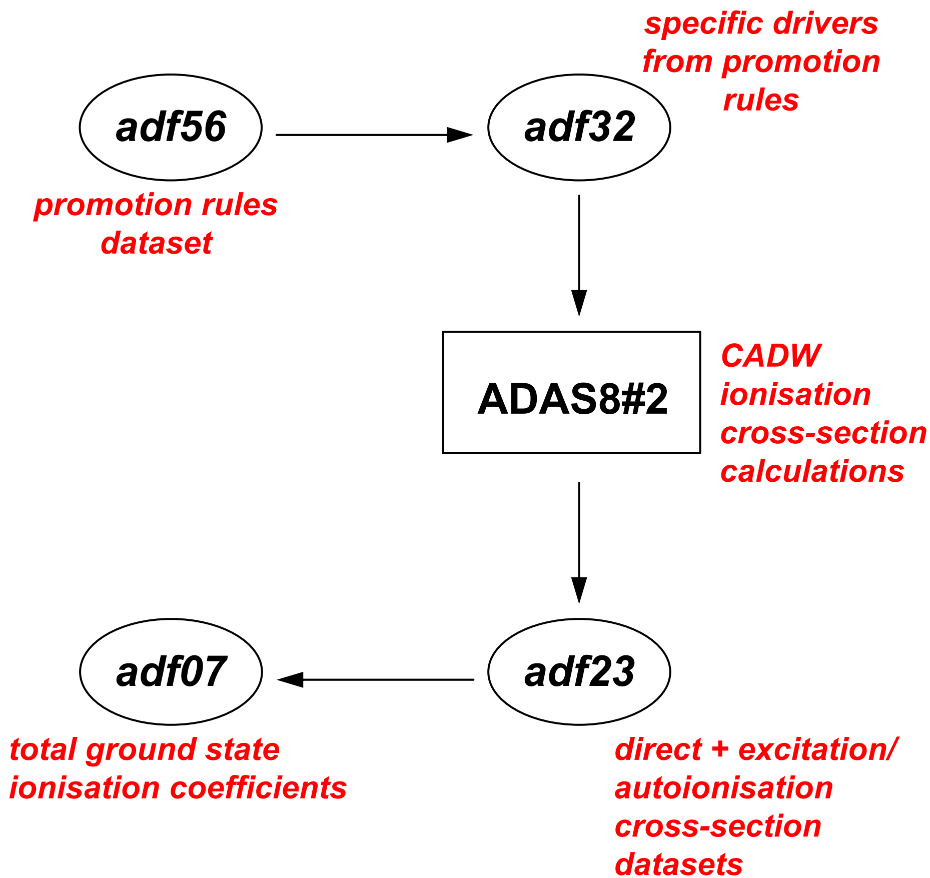


Silicon work

STEP 1 - *Revised adf04 for Si*

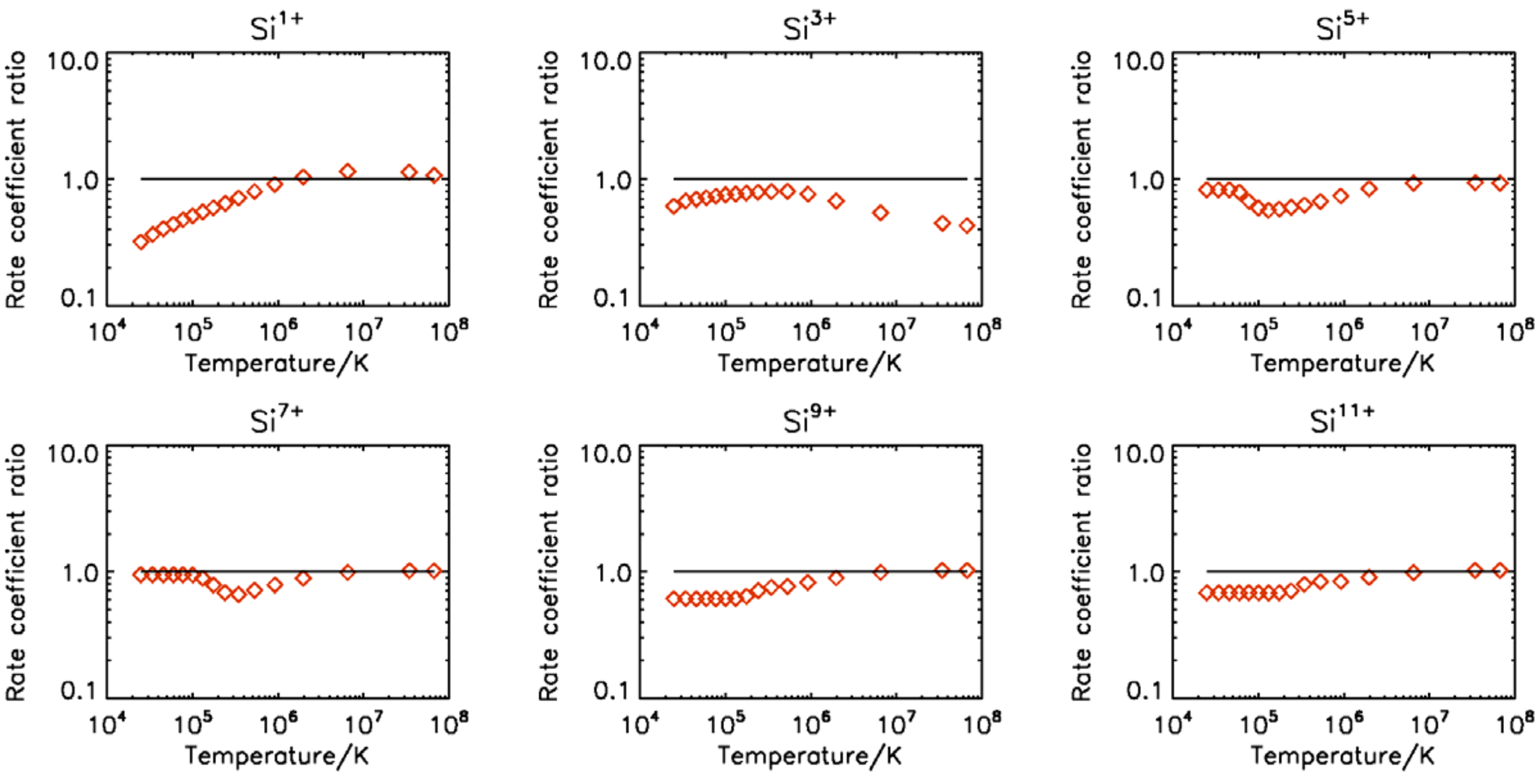
Si^{0+}	Cowan calculations
Si^{1+}	Dufton & Kingston (1991)
Si^{2+}	Griffin et al. (1990)
Si^{3+}	Liang et al. (2009)
Si^{4+}	Bhatia et al. (1985)
Si^{5+}	Witthoeft et al. (2007)
Si^{6+}	Bhatia & Landi (2003)
Si^{7+}	Bhatia & Landi (2003)
Si^{8+}	Bhatia & Doschek (1993)
Si^{9+}	Liang et al. (2009)
Si^{10+}	Bhatia & Landi (2007)
Si^{11+}	Zhang et al. (1990)
Si^{12+}	Zhang & Sampson (1987)
Si^{13+}	Sampson et al. (1983)

STEP 2 - *Ionisation rates*



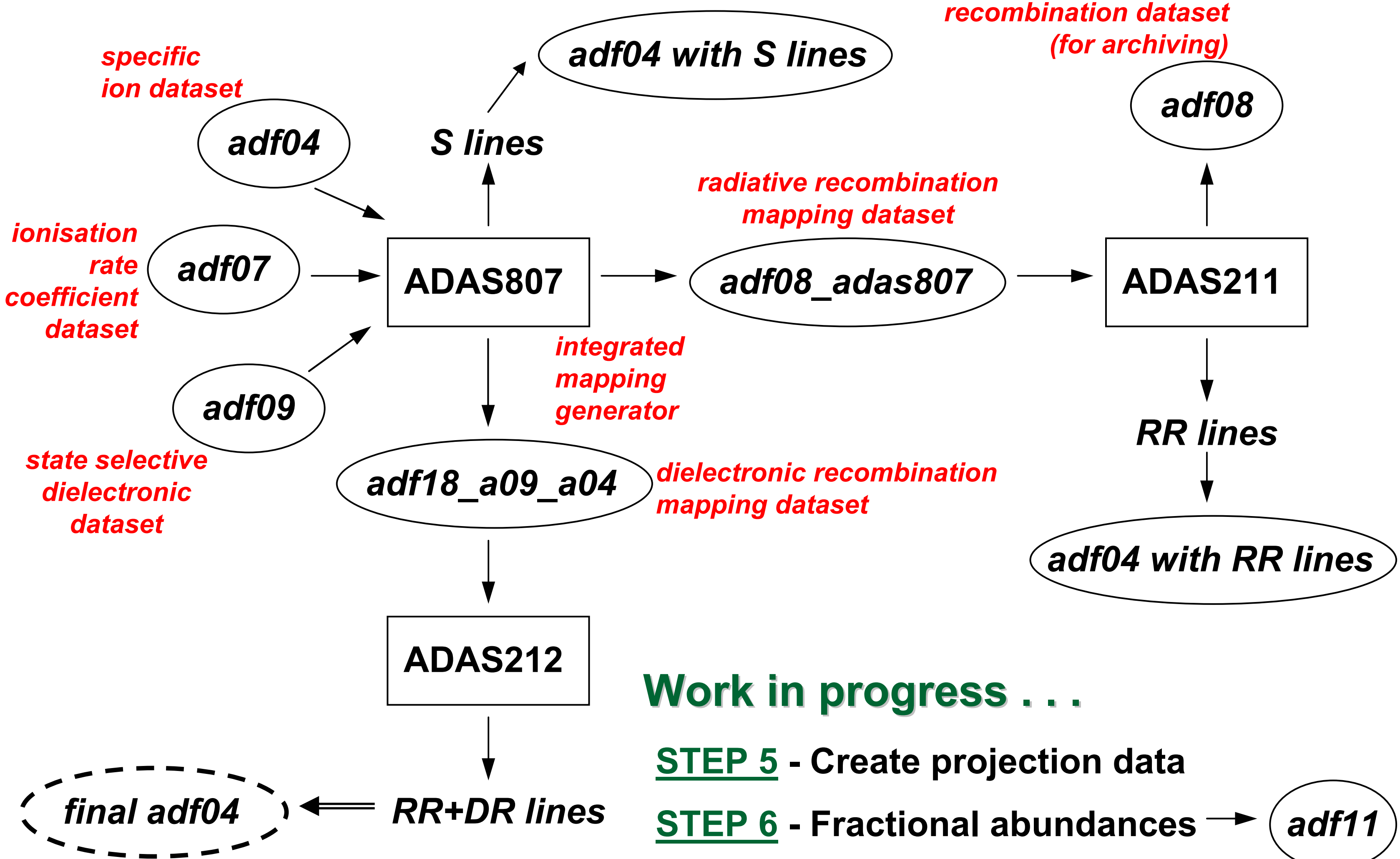
Silicon work

STEP 3 - ***Comparison with Dere (2007) ionisation rates***



Silicon work

STEP 4 - *Add S and R (RR+DR) lines to adf04*



Work in progress . . .

STEP 5 - Create projection data

STEP 6 - Fractional abundances

Future work

- Complete Si ionisation work and perform calculation for other elements of astrophysical interest, such as Mg
- Complete cross calibration for the new observations from the three different instruments (SUMER, CDS and EIS)
- Evaluate D.E.M. using the new observations and the updated atomic data
- Extend work to more active regions to investigate a possible connection with the stronger magnetic field
- Include opacity effects (full radiative transfer calculations)
- Examine how FIP (First Ionisation Potential) effect can affect the reconstructed intensities of He lines, since He is the element with the highest FIP (24 eV). As a consequence of its high FIP value, He lines show high excitation energies that make them very sensitive to non-equilibrium effects.