Improved atomic modelling for solar UV radiative transfer calculations

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(with acknowledgement to Pete Storey, UCL)

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Background

Far-UV wavelength range (900-1700Å) spectral features essential for understanding solar chromosphere and transition region

Synthetic spectrum continuum too intense by factors of 2-10 compared to observations.

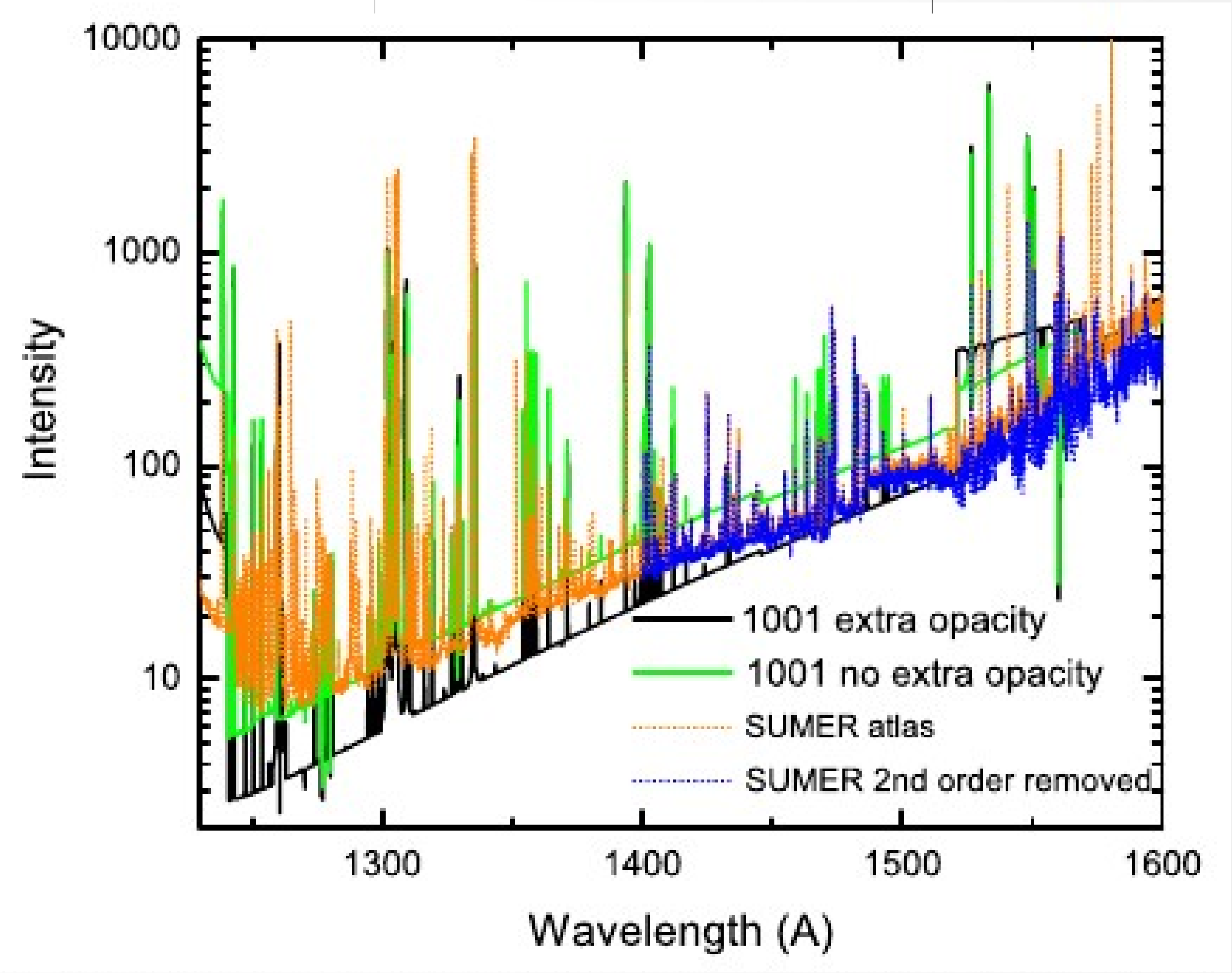
Example shown from Fontenla et al (2009).

Various solutions proposed to resolve this, such as ‘line blanketing’, ‘line haze’, ‘missing/extra opacity’, others call them fudge factors.

Rise from temperature minimum

Temperature minimum

Between photosphere and temperature minimum



Background

In general purpose codes, some atomic models have been shared around and some data have not changed since early radiative transfer calculations. Take RH for example.

THE ASTROPHYSICAL JOURNAL, 557:389–398, 2001 August 10

MULTILEVEL RADIATIVE TRANSFER WITH PARTIAL FREQUENCY REDISTRIBUTION

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Photoionisation and radiative recombination handled incorrectly

```
# Carbon I background version
# Data Mostly from TopBase:
#   D Luo & AK Pradhan, 1989, J. Phys. B, 22, 3377 (ADOC-11)

  C

# Nlevel  Nline   Ncont   Nfixed
   15      16      14       0

# Energy levels from C. E. Moore, NSRDS-NBS 35/Vol I

# Collisional rate coefficients from impact.c

 TEMP   7       3000.0    5000.0    7000.0   10000.0   20000.0   30000.0  100000.0

 CE     1  0   1.669E-15  1.418E-15  1.273E-15  1.136E-15  9.097E-16  7.990E-16  5.435E-16  (van Regemorter)
 CE     2  0   4.697E-16  3.989E-16  3.582E-16  3.195E-16  2.560E-16  2.248E-16  1.529E-16  (van Regemorter)
 CE     3  0   2.227E-16  1.891E-16  1.698E-16  1.515E-16  1.214E-16  1.066E-16  7.252E-17  (van Regemorter)
 CE     4  0   4.734E-15  2.854E-15  2.048E-15  1.443E-15  7.381E-16  5.027E-16  1.704E-16  (Seaton IP)
```

Missing atomic processes – dielectronic recombination
charge transfer

1960s approximations for collisions

Methods

OPEN ACCESS

The Astrophysical Journal, 917:14 (17pp), 2021 August 10 https://doi.org/10.3847/1538-4357/ac02be

CrossMark

The *Lightweaver* Framework for Nonlocal Thermal Equilibrium Radiative Transfer in Python

Christopher M. J. Osborne[1] and Ivan Milić[2,3,4]

- Start with old atomic models:

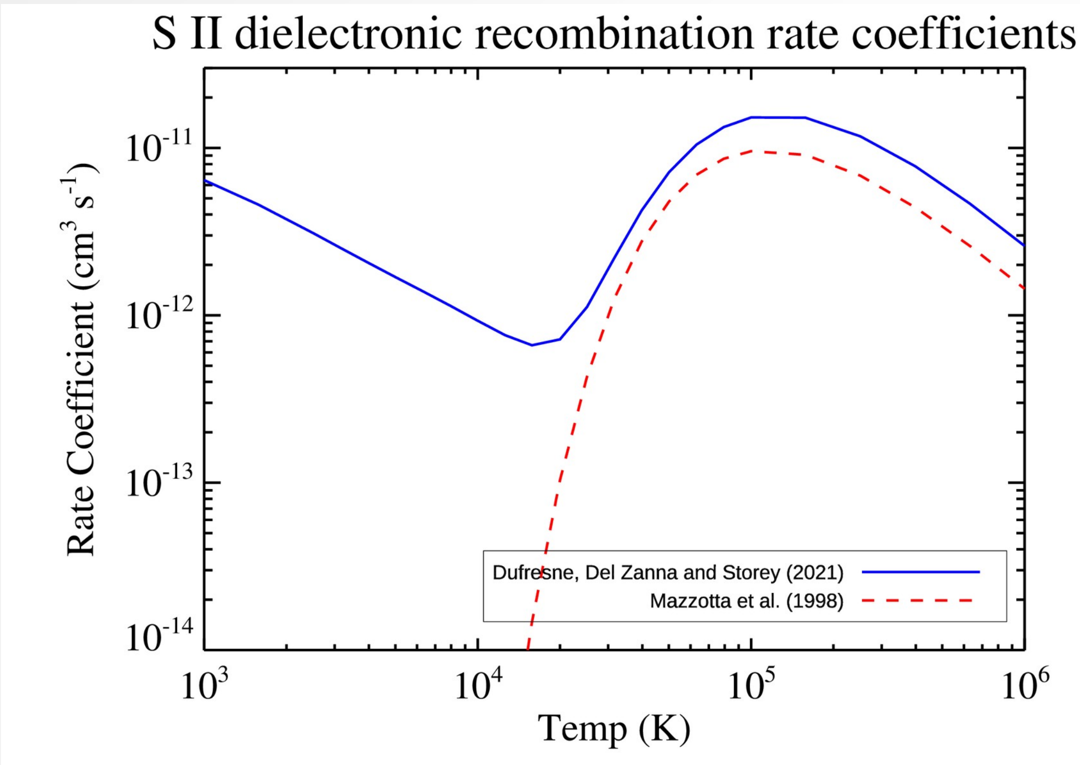
  - H, He, C, O, Mg, Al, Si, Fe in non-LTE

  - N, S, Ni in LTE.

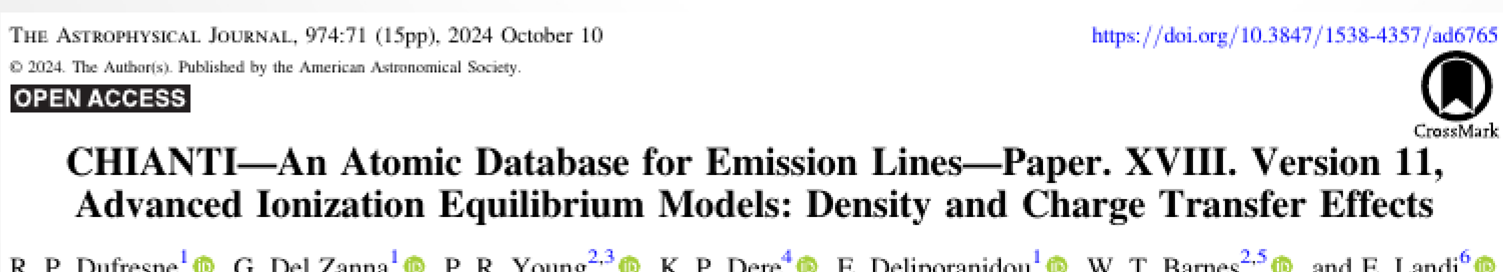
  All the models are taken from RH code and available in Lightweaver
- Fontenla et al. (2014) quiet Sun, cell model for the input atmosphere
- Use 1D radiative transfer so that we can assess impact of improving atomic processes separately from dynamic processes, 3D effects, etc.
- Assess results against averaged, quiet Sun observations of continuum from Samain et al (1975, 1979) sounding rocket because of discrepancies in SUMER at longer wavelengths
- Use this as a baseline to compare results with new models we created

Methods

Build entirely new models for C, Si and S to cover 1100-1700Å wavelength range



Burgess (1965) general formula for dielectronic recombination (DR) only suitable for coronal temperatures. Use DR Project data (Badnell et al. 2003), which includes low temperature DR.


The Astrophysical Journal, 974:71 (15pp), 2024 October 10
https://doi.org/10.3847/1538-4357/ad6765

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CHIANTI—An Atomic Database for Emission Lines—Paper. XVIII. Version 11, Advanced Ionization Equilibrium Models: Density and Charge Transfer Effects

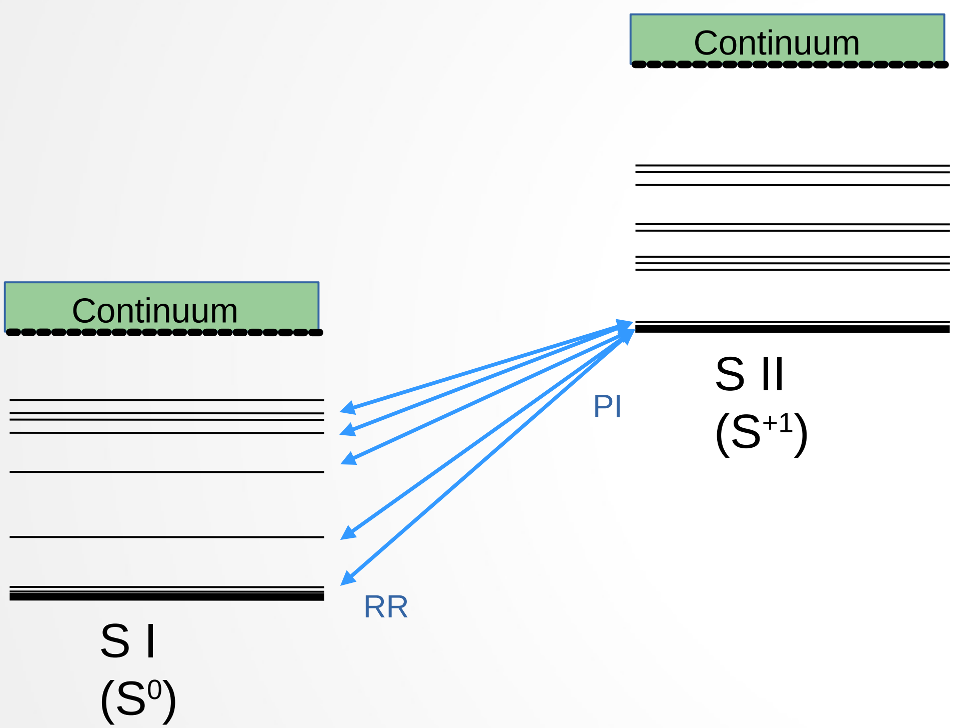
R. P. Dufresne[1], G. Del Zanna[1], P. R. Young[2,3], K. P. Dere[4], E. Deliporanidou[1], W. T. Barnes[2,5], and E. Landi[6]

CHIANTI v11 for charge transfer, collisional excitation, radiative decay, level energies

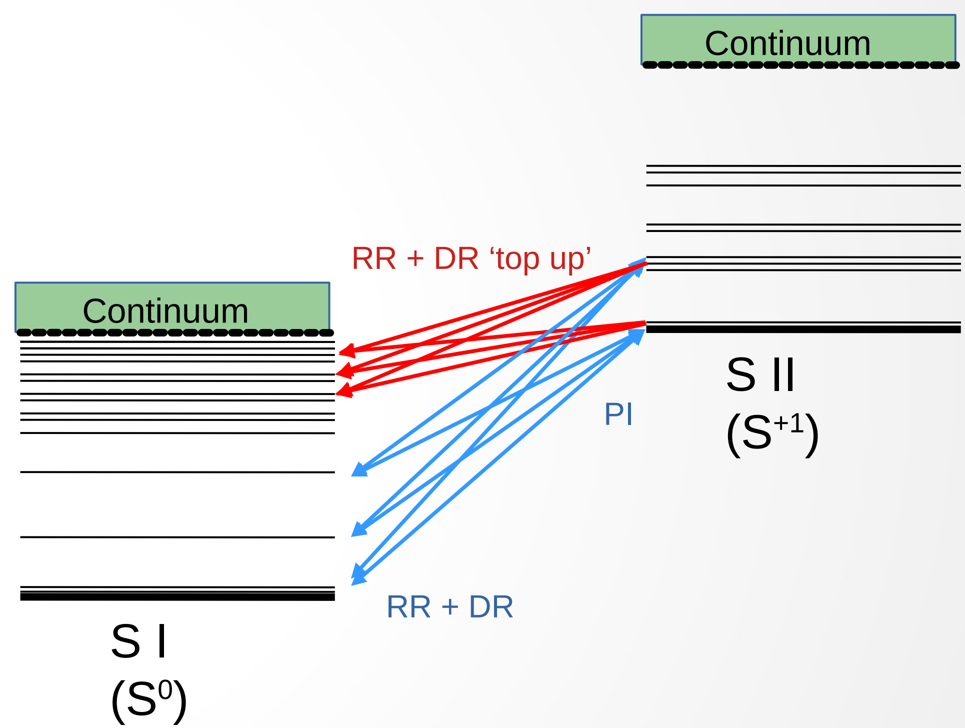
Methods

Even good data handled incorrectly – such as photo-ionisation (PI) and radiative recombination (RR)

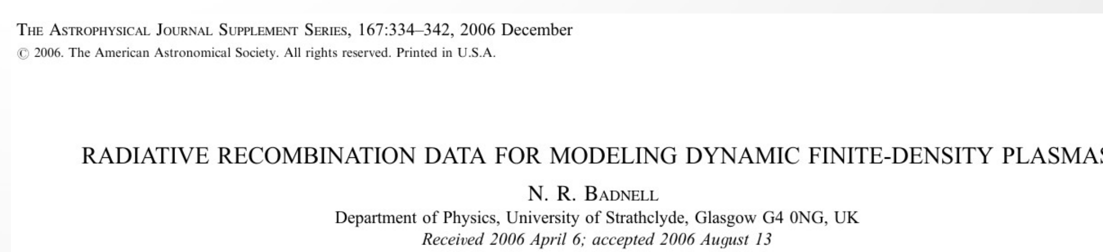
Existing codes



Fully level resolved treatment



Many old codes use Opacity Project (OP, Seaton 1995) total cross sections



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RADIATIVE RECOMBINATION DATA FOR MODELING DYNAMIC FINITE-DENSITY PLASMAS

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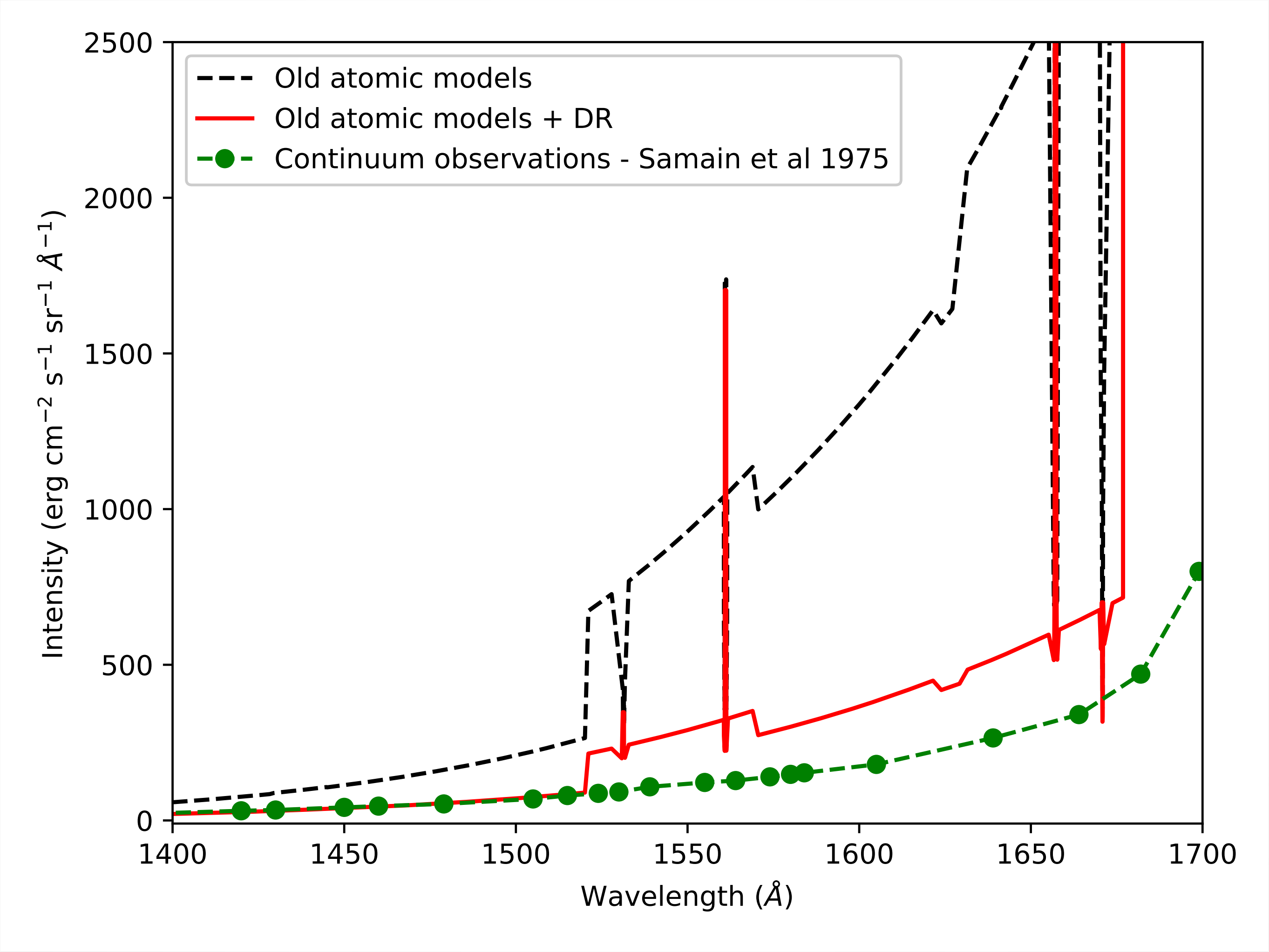
Results

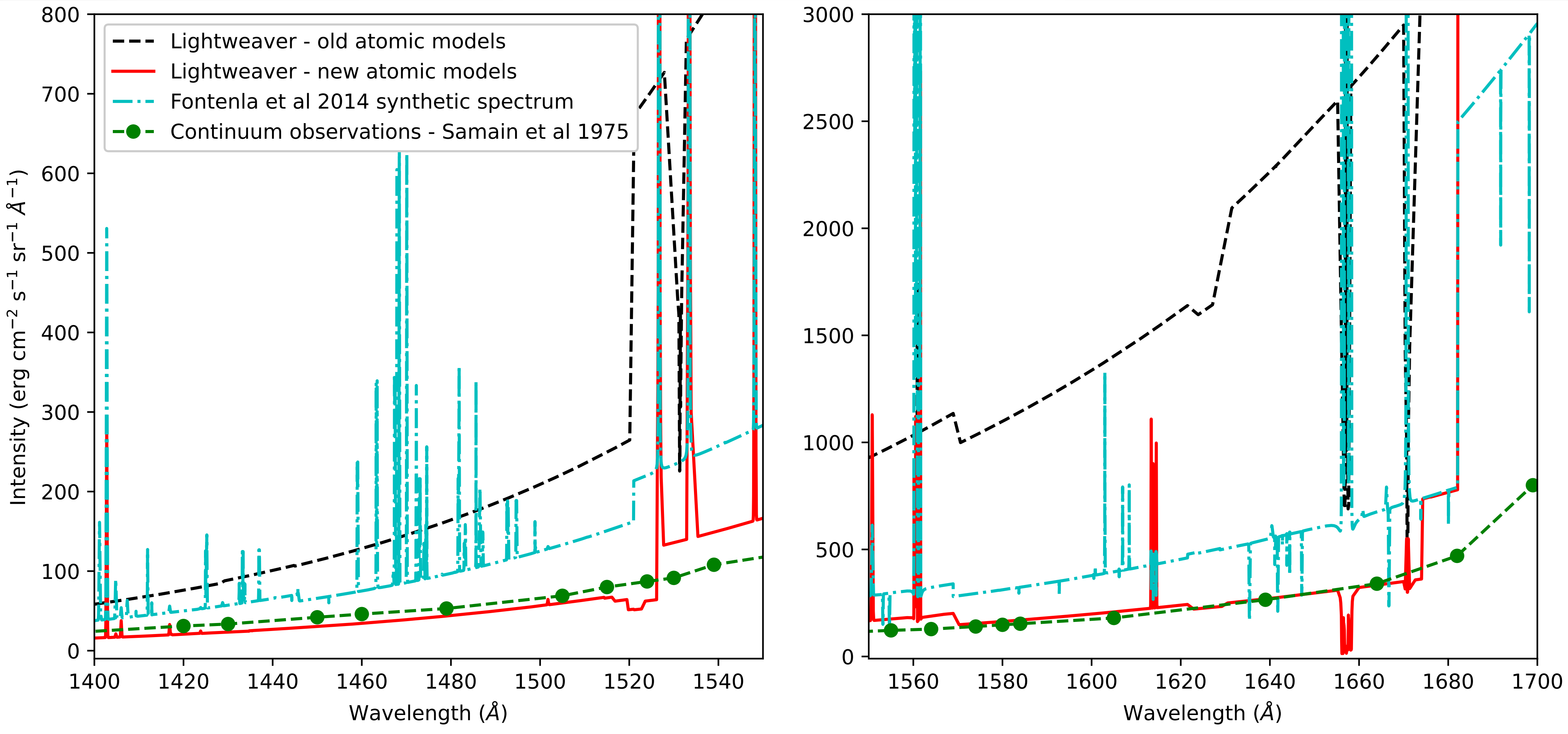
Adding level resolved photo-ionisation (LR PI) and radiative recombination (RR) 'top up' to old atomic model for Si



Greater presence of Si^0 following recombination leads to more absorption of blackbody spectrum

Results - continuum

Si continua from new atomic models in much better agreement with observations of UV continuum



Fontenla et al. (2014) included missing opacity, which reduced continuum intensity by factor of 2. Missing opacity is not included in Lightweaver and is not needed with new atomic models.

Summary

I Used updated atomic data for charge transfer, photo-ionisation, radiative and dielectronic recombination, collisional excitation, radiative decay. Included DR suppression

II Notable changes in ion formation caused by new atomic processes and treating existing processes correctly

III Very good agreement for continuum in synthetic spectrum compared to observations when using new atomic models

Implications and future work

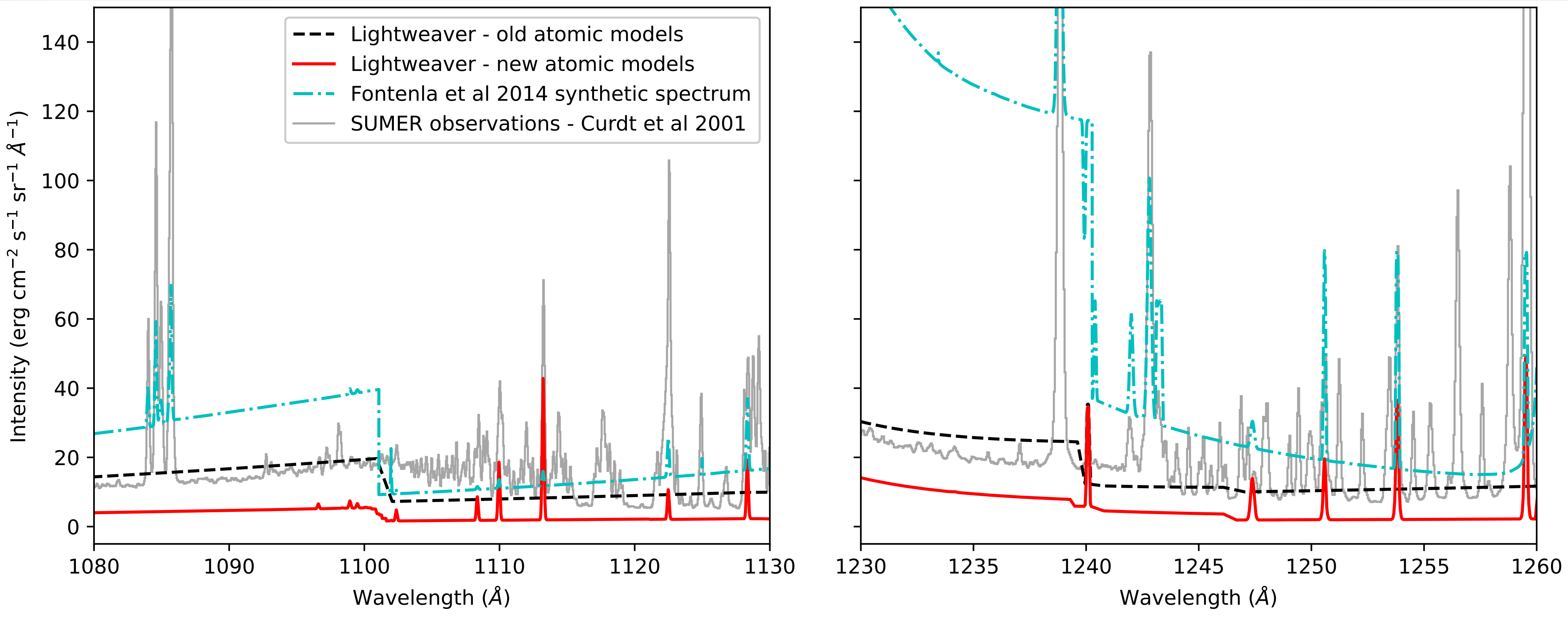
IV Parameters derived in model atmosphere calculations may change if this type of atomic modelling is used

V Relevant for other solar conditions and where 3D effects and time dependent ionisation are important, such as active regions and flares

VI Relevant for many radiative transfer codes including stellar astrophysics and the new SAMS project (see Andrew Hillier talk Thurs am)

Results

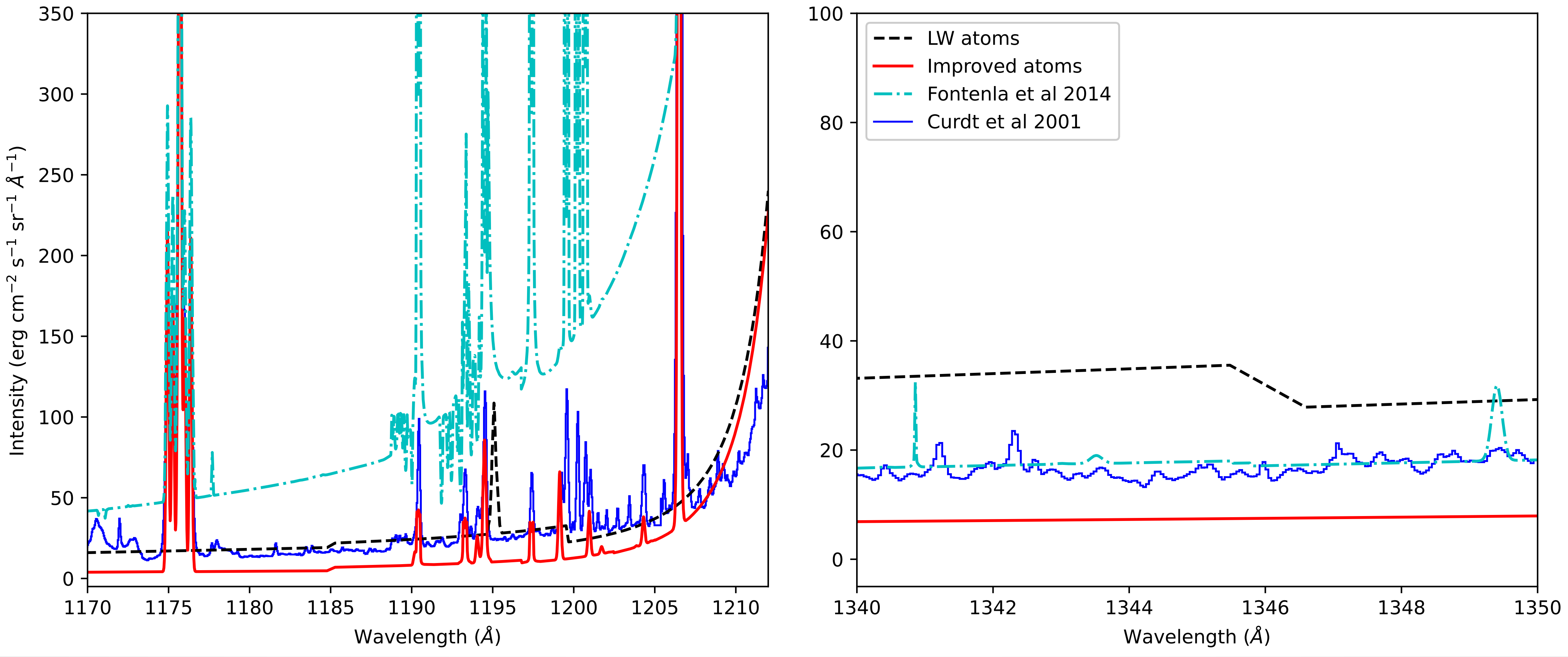
C continuum from new atomic models compared with old atomic models, Fontenla et al (2014) synthetic spectrum and quiet Sun, averaged SUMER observations



Raises question whether model atmosphere would be different if present atomic modelling had been used.

Results

New atomic model for S compared with Lightweaver default atomic model and Fontenla et al (2014) synthetic spectrum



Results

Correcting treatment of radiative recombination (RR) process

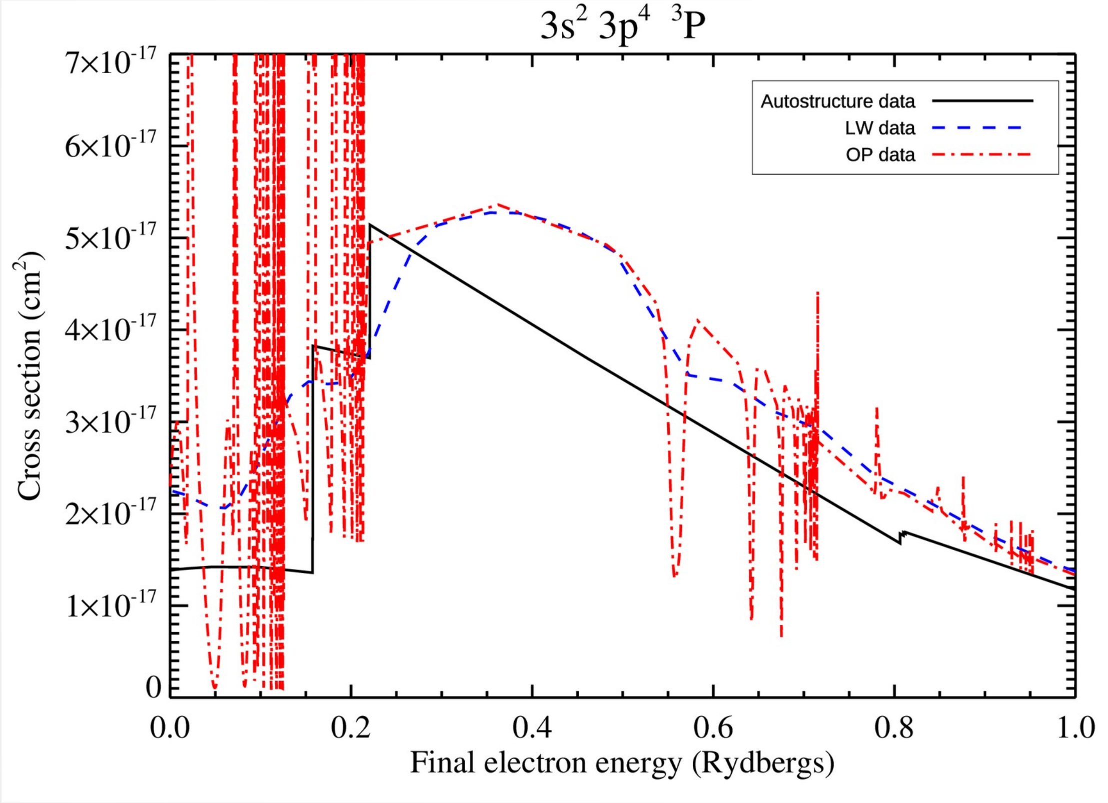
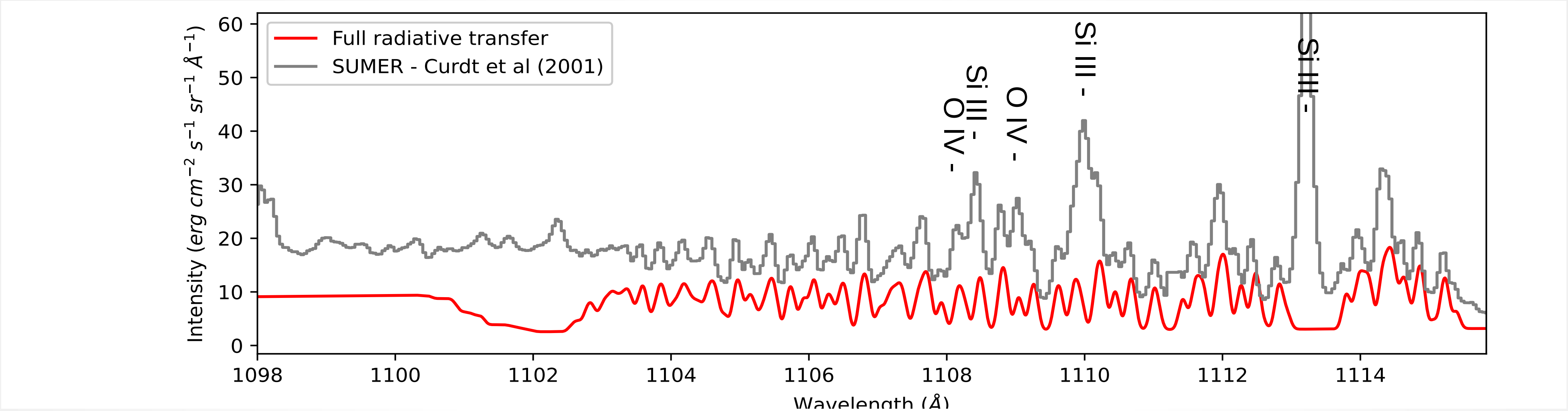


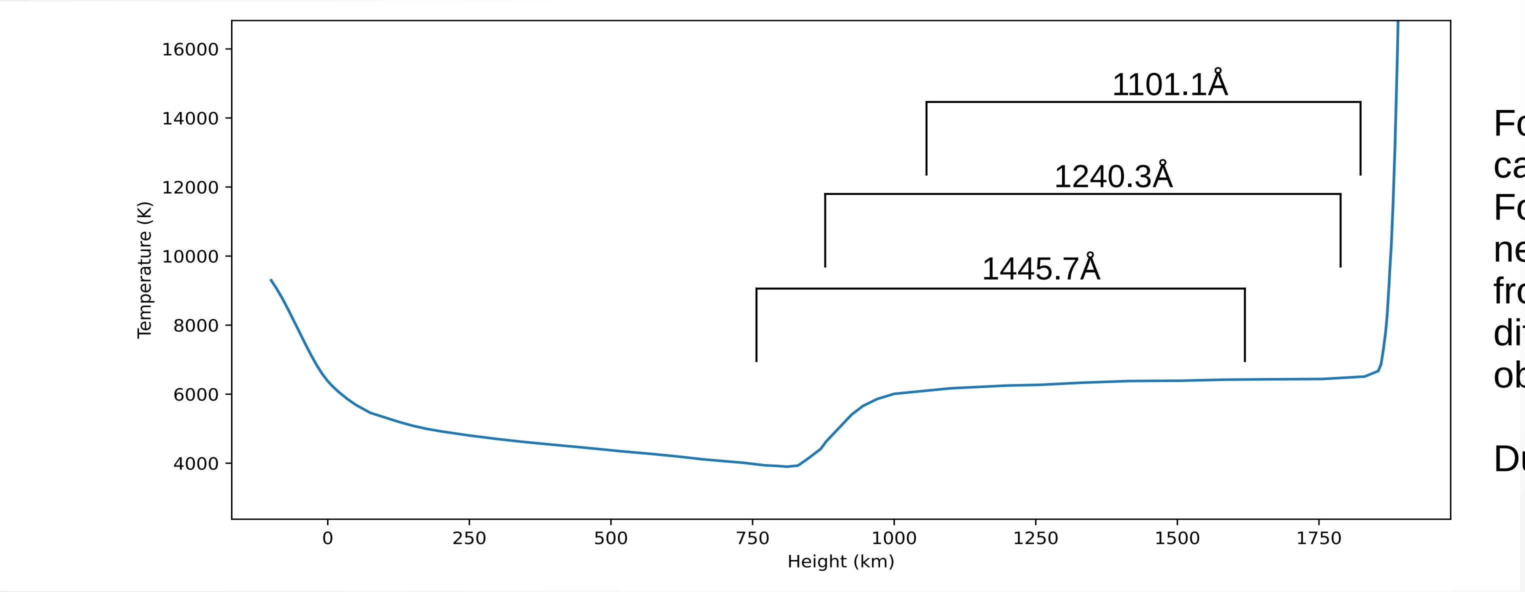
Table 4. Comparison of RR rates from the base and improved models (in s^{-1}) from all terms in the $3s^2\,3p^3$ ground configuration of S^+ at two different temperatures. The fractional populations of each term according to the improved model are also given.

Model	^4S	^2D	^2P
At 3750 K			
Lightweaver	0.058	-	-
Improved	0.037	0.035	0.045
Fractional population	0.99	0.01	10^{-4}
At 20 000 K			
Lightweaver	0.022	-	-
Improved	0.009	0.007	0.009
Fractional population	0.47	0.41	0.12

Results

Using recent atomic data (Storey, Dufresne, Del Zanna, 2023) to develop new diagnostics for chromosphere – relevant for Solar C EUVST (talk given at NAM Mon am)





Formation heights of the neutral carbon Rydberg lines in the Fontenla et al (2014) quiet Sun network model. Rydberg lines from other elements form at different heights and will be observed by Solar-C.

Dufresne et al., 2025, in prep.