

Developments in Soft X-Ray Spectral Modelling for Fusion: Areas of Overlap with Astrophysics

Allan D Whiteford

with

N R Badnell, R Barnsley, I H Coffey

M G O'Mullane, H P Summers and K-D Zastrow

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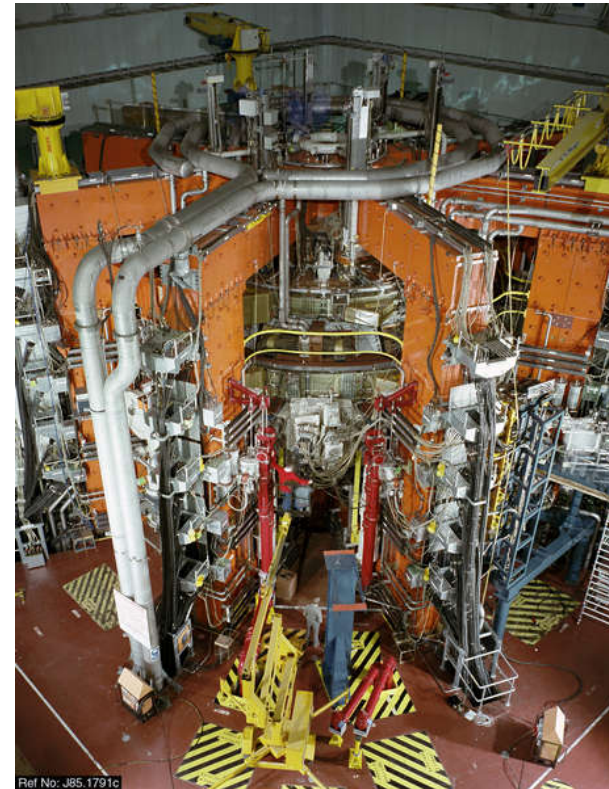
Introduction

- Clear similarities and differences between analysis of fusion and astrophysical plasmas.
- Atomic modelling techniques routinely used in fusion
- Recent developments for fusion relevant to the soft x-ray region.
- Overlaps with astrophysical analysis
- Discussion on possible overlaps and shared work.

Disclaimer: a European/ADAS perspective of (magnetically confined) fusion

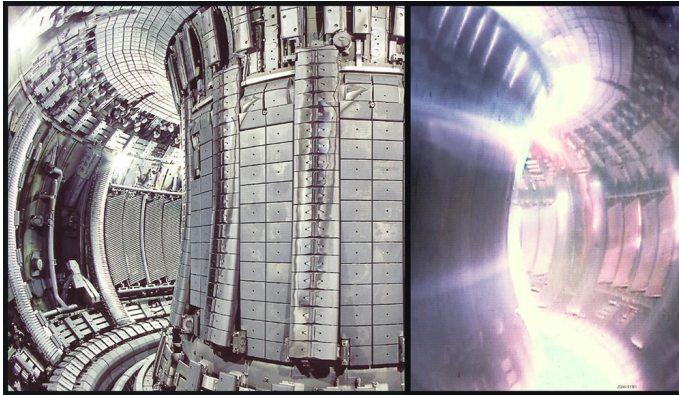
Fusion versus astrophysical diagnostics

- Active diagnostics
- Multiple lines of sight and bolometry
- Much shorter observation times
- Less unknowns
- More than spectroscopy available

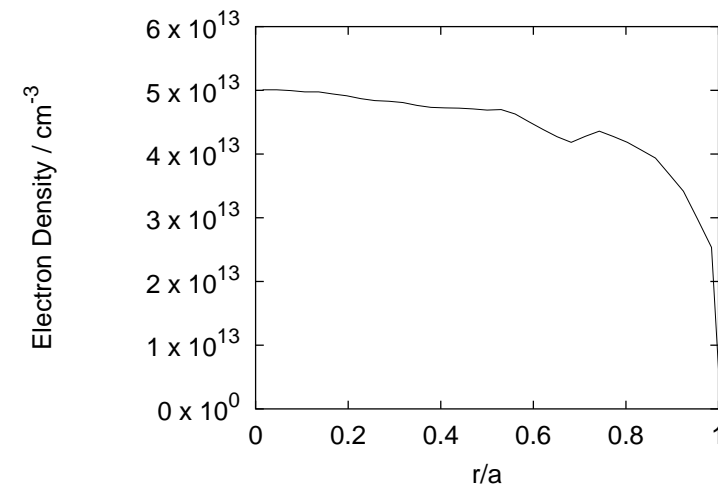
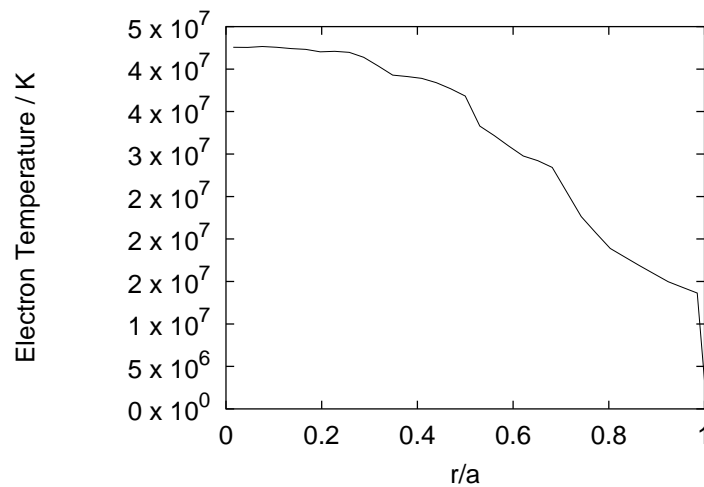


But greater accuracy is expected and required.

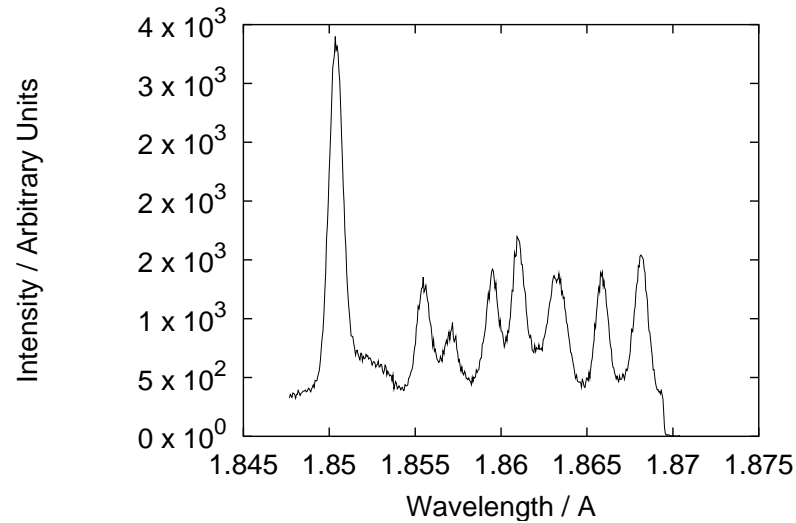
Fusion plasmas: a regime overview



- Temperature: $10^5\text{K} — 10^8\text{K}$.
- Density: $10^{10}\text{cm}^{-3} — 10^{15}\text{cm}^{-3}$
- Magnetic field: Up to 5T

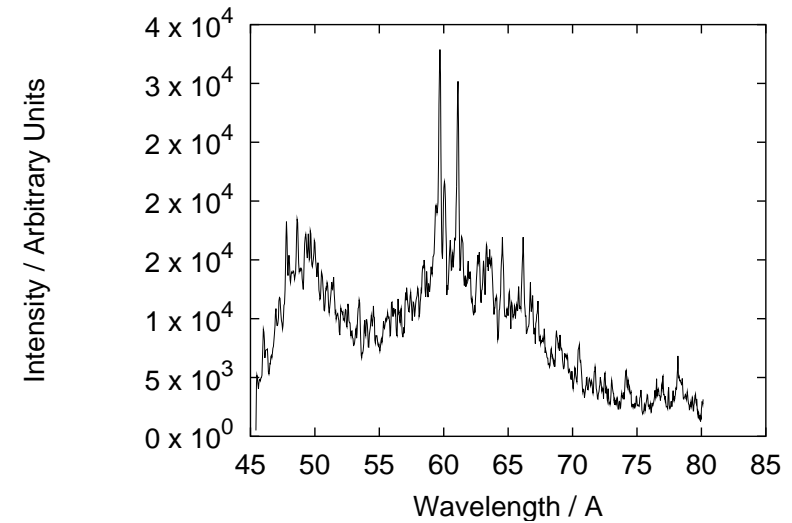


Measurements: from individual lines to a quasi continuum



Familiar

Helium-like iron with associated lithium-like satellite lines, measured on TEXTOR.

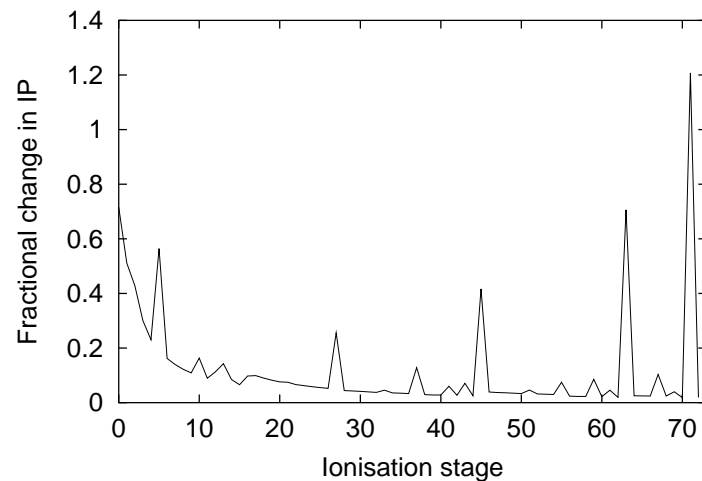


Less familiar

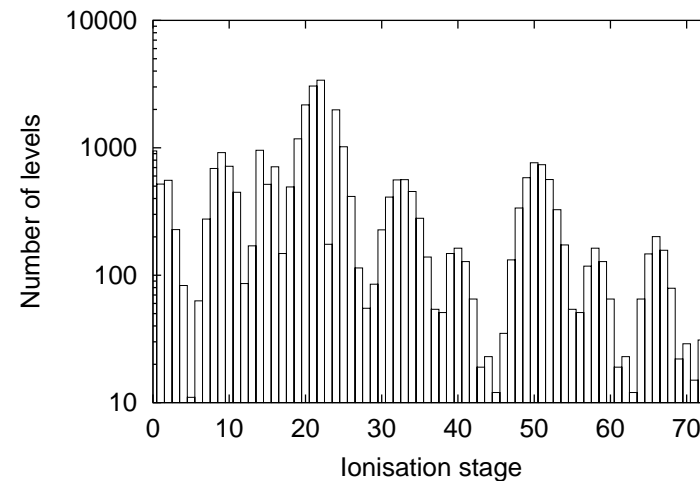
A quasi-continuum spectrum from tungsten, measured on JET.

Baseline fundamental atomic data

- Use a plane-wave Born approach for systematic coverage



Fractional change in ionisation potential as a function of charge

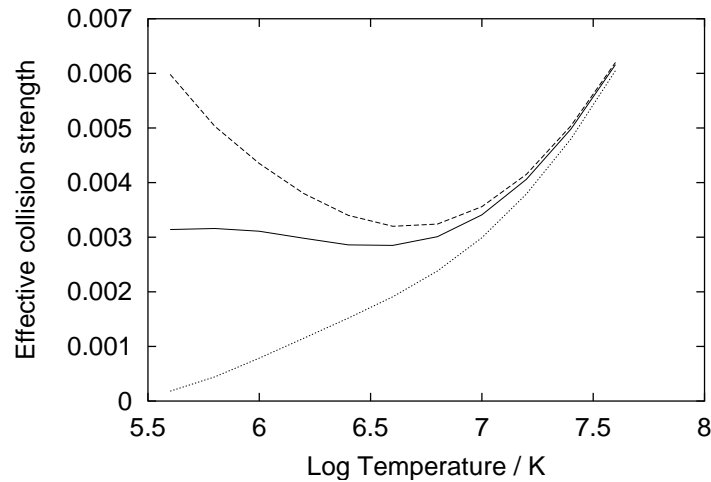


Number of levels for a typical tungsten calculation

- System allows selective upgrading of data from better methods.

High quality fundamental atomic data — light species

- R -matrix can now be used routinely for light species giving rise to x-rays with the inclusion of key 'non-standard' effects.



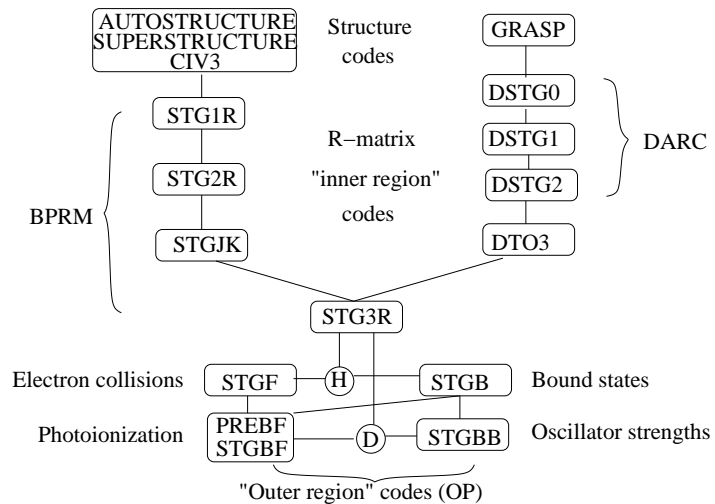
Temperature	$3 \times 10^5 \text{K}$		$3 \times 10^7 \text{K}$	
Contribution	ADI	ADE	ADI	ADE
Background	9.48		9.51	
$1s2s2pnl$	0.92	2.92	—	—
$1s2s3l3l'$	—	—	0.49	0.49
$1s2s3l4l'$	—	—	0.20	0.22
$1s2s3l5l'$	—	—	0.24	0.26
$1s2s3lnl'$	—	0.11	0.02	0.69
Total	10.4	12.5	10.4	11.2

Radiation damping in he-like Ar

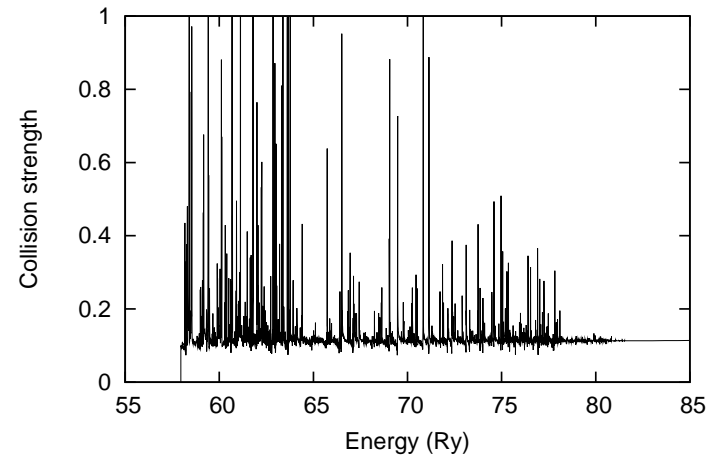
Auger damping in li-like Fe

High quality fundamental atomic data — heavy species

- We use the Dirac Atomic R-matrix Code (DARC) within our current system, getting damping, parallelisation etc. for 'free'.



Flow diagram of DARC procedure



$3d^{10} \ ^1S_0 - 4d \ ^1S_0$ transition in Xe^{26+} , emits in the x-ray at ~ 18 Angstroms

Key deliverables for plasma analysis

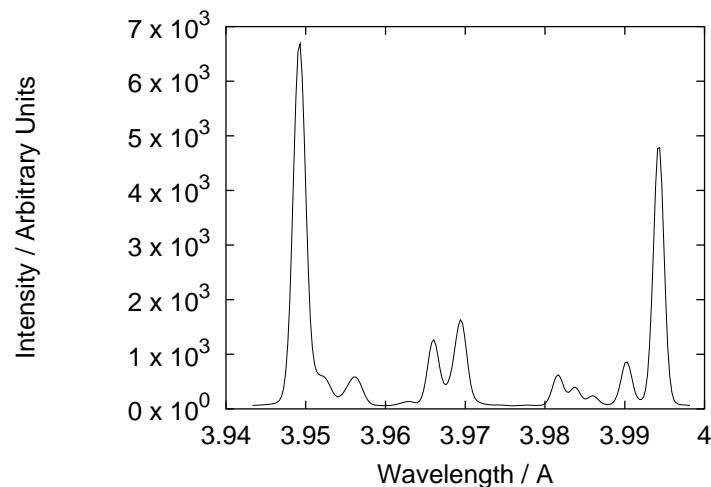
- Effective ionisation, recombination and power coefficients.*
- Photon emissivity coefficients.*
- The most widely used database (part of the ADAS Project) currently contains data for:
 - Recombination, ionisation and power coefficients for most ions.*#
 - Line emission coefficients for more than 15,000 lines.*#
 - A capability to calculate data at varying levels of sophistication for any ion.
- Deliverables are not cross sections!

* Density dependence necessary.

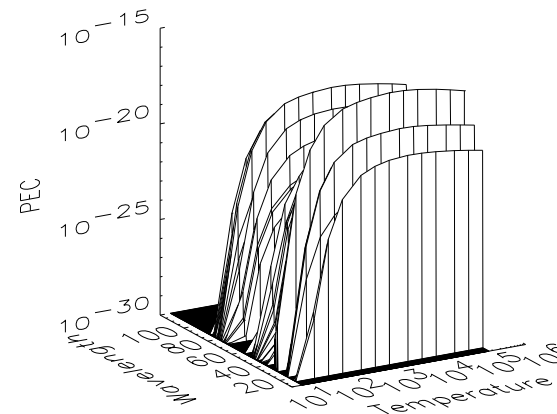
Elaborated for light ions, metastables etc.

Spectral synthesis and special feature analysis

- The approach for complex spectra are to forward model special features:
 - Better than fitting Gaussians and taking line ratios.
 - Smooth progression into continuum analysis and low resolution spectra.



Helium-like argon.

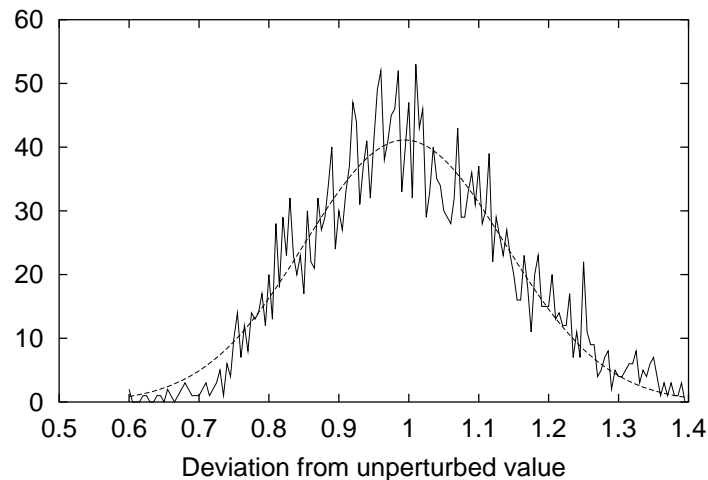


Tungsten at $n_e = 10^{14} \text{cm}^{-3}$

Error propagation in the collisional-radiative model

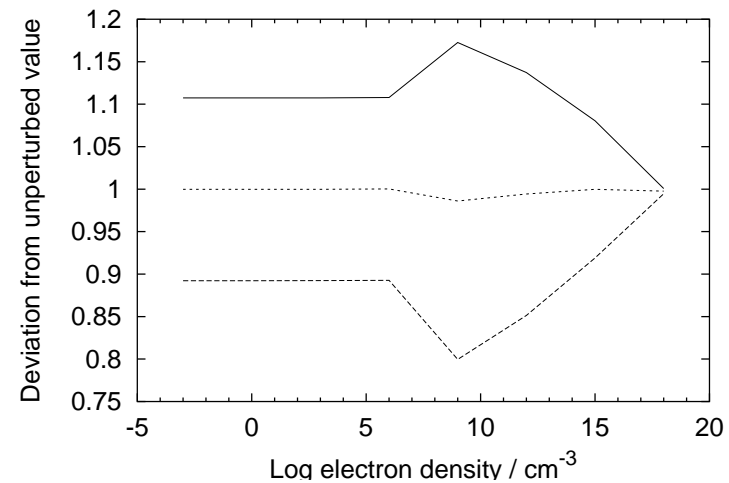
- We use Monte-Carlo sampling to propagate errors in effective collision strengths through to a finite-density population structure, leading to the error in plasma models when compared with experiment.
- A complementary method shows sensitivity of specific populations to specific transitions in T_e/n_e space. This allows transitions which need refinement to be easily identified.
- The full Monte-Carlo approach is useful for astrophysical plasmas in the finite density regime but less so if the low density limit can be assumed. Error propagation is still necessary.
- This technique critically relies on having estimates of uncertainty on fundamental atomic data.

Uncertainty in the population of the $1s2s\ ^3S_1$ level in Fe^{23+} .



- Propagated errors are dependent on density and temperature.
- Model and error propagation move through coronal, CR and LTE regimes.

- Gaussian errors in fundamental data give almost Gaussian errors in populations.
- Typically, more than 1000 samples are necessary to give a reliable error estimate.



Joint areas of work in the future

- Methods used in fusion analysis, with instrument resolution similar to new astrophysical measurements can be used.
- Atomic data produced for astrophysics should be made relevant to fusion (e.g. not just doing astrophysical species)
- Atomic data produced for fusion should be made relevant to astrophysics (e.g. not just doing fusion-relevant species)
- Uncertainties/error bars on fundamental atomic data are critical. Both fusion and astrophysical modellers can (should!) push for this.