ASOS14, Paris, 11 July 2023

Atomic astrophysics with 3D non-LTE stellar spectroscopy Anish Amarsi (Uppsala University)

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- well-constrained at the end of the 20th century
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The solar chemical composition

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The solar chemical composition

Physica Scripta. Vol. **T47,** 133-138, 1993

Atomic Data and the Spectrum of the Solar Photosphere

Grevesse and A. Noels

Institut d'Astrophysique, Université de Liège, 5, avenue de Cointe, B-4000 Liege, Belgium

Received October 14,1992; accepted in revised form February 12,1993

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The solar chemical composition

Example stellar spectra [Nissen & Schuster 2010]

Much smaller line-by-line scatter when they used improved oscillator strengths

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The solar chemical composition **3.6** *0.00* **0.50 1.00 pkw I50 Fig. 2. Abundance of vanadium as a function of the excitation energy** derived by different authors [44-461 and present results [43-461 and present results [43], using different results [43-461 and present results [43-461 and present results [43-461 and present results [43], using different r

Much smaller line-by-line scatter when they used improved oscillator strengths

(In this plot: Blackwell et al. 1987)

Evolution of solar iron abundance with improving log gf data [Grevesse & Noels 1993]

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Space Science Reviews 85: 161-174, 1998. © 1998 Kluwer Academic Publishers. Printed in the Netherlands.

STANDARD SOLAR COMPOSITION

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N. GREVESSE and A.J. SAUVAL Institut d'Astrophysique et de Géophysique, Université de Liège, B-4000 Liège, Belgium $(nicolas, greves se @ulg. ac. be)$ Observatoire Royal de Belgique, B-1180 Bruxelles, Belgium (Jacques. Sauval@oma.be)

The solar chemical composition

- However, 1990's analyses were based on simple 1D LTE models:
	- Grevesse & Sauval 1998, Z=1.69%
- Reality: stellar atmospheres are 3D non-LTE

The revised solar chemical composition **A. M. Amarsi*****

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2016 Sep 19 09:01:00.000 (TAI) **SDO/HMI + SST view of the Sun [J. Leenaarts & J. de la Cruz Rodriguez, Stockholm; NASA Scientific Visualisation Studio]**

Simulations (Stagger code)

1D model

1D model

1D model

1D models need various fudge parameters to try to account for 3D effects and hide important physics e.g.

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- **• Macroturbulence**
- **• Mixing length parameters**
- **• Convective blueshift**

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• Line asymmetries

1D model

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eakening **1D models need various fudge parameters to try to account for 3D effects and hide important physics e.g. • Microturbulence • Macroturbulence • Mixing length parameters • Convective blueshift • Line asymmetries • Line strengthening/weakening**

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LTE versus non-LTE

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After the same above the same above the same above the same above the same of the same of the same of the same **Lithium 671nm line in a metal-poor subgiant [Lind+ 2013]**

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Accuracy atomic data, in particular oscillator strengths, photoionisationisationisationisationisationisationisationisationis

Atomic data needs The oriental Astrophysics, Department of Physics and Astrophysics and Astronomy, Uppsala University, Box

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SPECTROSCOPY A. M. Amarsi*** **3D RHD simulations: opacities, partition**

atomic data, in particular oscillator strengths, photoionisationisationisationisationisationisationisationisationis **Accuracy**

SPECTROSCOPY 3D RHD simulations:

This information sheds in the structure and experience and evolution of the structure and evolution of the structure and evolution of the stars themselves, and the stars themselves, as well as well as well as well as well **High precision spectroscopy:** 0 **wavelength; BB transition rate; broadening parameters; HFS**

SPECTROSCOPY A. M. Amarsi*** \blacksquare **Functions (EOS) 3D RHD simulations: opacities, partition**

Full NI atom 230 levels 4186 lines 554 continua

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Databases (not exhaustive): Atomic data needs **• NIST** Theoretical Astrophysics, Department of Physics and Astronomy, Uppsala University, Box $\overline{116}$ **• OP/IP** \mathcal{S} stars leave the light their signatures on the light theorem they emit from the form of \mathcal{S} **• Kurucz**absorption and emission lines. By comparing with model stellar spectra, we can decode the spectra, we can decod signatures to reveal the physical properties of stars, in particular their chemical compositions. This information sheds light on the structure and evolution of the stars themselves, as well as w their planets, and even the Galaxy as a whole... provided that the model spectra are sufficiently as a whole.. 14 12 0.6 −4 10 log_{10} [C / Max (C)] −3 Height / Mm 0.4 Energy / eV P. E. Nissen and W. J. Schuster: Two distinct halo populations in the solar neighborhood −4 Energy / eV −2 8 Σ 0.2 −1 \circ $6⁺$ −6 $\overline{+0}$ log. \mathbf{H} \blacksquare 0 4 \mathcal{H} −8 Full NI atom −0.2 2 230 levels Fel 4186 lines 554 continua −10 0 $\varphi_{\bf p}$ 1. 2. $_{\rm cri}$ 3. 4. \blacksquare 5. 2 S $^{\circ}$ 2 P $^{\circ}$ 2 P $^{\circ}$ 2 2 D 2 2 D $^{\circ}$ 2 $\rm ^2F$ $\rm ^2$ 2 F $^{\circ}$ 2 G 2 G $^{\circ}$ 4 $\mathrm{^{4}S^{o}}$ $\mathrm{^{4}}$ $\rm ^4P$ $\rm ^4$ 4 P $^{\circ}$ 4 $^4{\sf D}$ $^4{\sf D}^{\rm o}$ $^4{\sf F}$ $^4{\sf F}^{\rm o}$ $^4{\sf G}$ $^4{\sf G}^{\rm o}$ x / Mm **Figure 1:** 3D non-LTE modelling of N I lines in the solar atmosphere [2]. *Left:* Term diagram illustrating the levels and transitions considered in statistical equilibrium. *Right:* Contribution $\begin{equation} 0.6 \begin{array}{ccc} \text{-} & \text{N} & \text{N} \end{array} \end{equation}$ 0.5 and the state-of-the-art in modelling the spectra of late-type state-of-type state-of-type stars like our Sun. Superior $\frac{1}{5688}$ 56 $\frac{1}{\sqrt{2}}$ radiation-dimensional (3D) radiation-dimensional (3D) radiation-dimension-dimension-dimension-dimension-

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	-
	-

Atomic data needs

−2 **including those produced by people here)**0 **(Plus data found scattered in the literature,**

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The revised solar chemical composition **A. M. Amarsi***** Theoretical Astrophysics, Department of P

- However, 1990's analyses were based on simple 1D LTE models:
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- Reality: stellar atmospheres are 3D non-LTE
- More realistic 3D/non-LTE modelling presented in 2005, refined in 2009, 2015, and most recently in 2021:
	- Asplund, Amarsi, Grevesse 2021, $Z=1.39%$

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- 3D/non-LTE modelling: downwards revision of solar metallicity
	- Grevesse & Sauval 1998: Z=1.7%
	- Asplund, Amarsi, Grevesse 2021: $Z=1.4%$
- Revealed a severe discrepancy between solar interior structure models and helioseismic inferences
- Worrying broader implications for (stellar) astrophysics

The solar modelling problem

Power spectrum of the Sun [W. Ball, Birmingham]

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Error in the predicted interior sound speed [Stasińka+ 2012]

72 Oxygen in the Universe The solar modelling problem

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Inlikely, because direct inversions of helioseismic data also suggest

_~1.4% consistent with 3D non-LTE models (Buldgen et al. submitted) <u>Didde an cel miversions</u> of henoscismic data anso straight.
The low-Z and low-Z

Best estimate of Z directly from helioseismic data [Buldgen+ submitted]

- A possible contributing factor to the solar problem is the treatment of interior opacities
	- Temperatures of around 2 million kelvin
	- Larger abundances or larger opacities = similar impact on solar models
- (Also see talk #4 on Monday; poster #26)

Figure 3 [|] Comparisons of iron opacity spectra with multiple models at the solar radiation/convection zone boundary temperature. The T^e 5 2.113 106K, n^e 5 3.13 1022 cm2³ conditions displayed here were the experiment error bars represent 1s uncertainties. a, Comparison with the Higher-than-predicted measured opacities [Bailey+ 2015]

SINCL A problem of missing opacity?

• "The measured wavelength-dependent opacity is 30–400 per cent higher than predicted. This represents roughly **half the change** in the mean opacity needed to resolve the solar discrepancy, even though iron is only one of many elements that contribute to opacity" [Bailey+ 2015] Data ede
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م \overline{z} P 2*p* to 4*d* a waveleng • "The measured wavelength-dependent opacity is 30–400 per cent higher at the solar radiation \mathbf{r} radiation \mathbf{r} than predicted. This represents re combine information from five separate experiments with four independent with four independent of the separate
The combine separate experiments with four independent of the separate experiments with the separate experimen many elements that contribute to $\frac{1}{2}$ y nan me change in me mean opacity opacity to the opacities modelled by SCRAM, OP and SCO-RCG.

Higher-than-predicted measured opacities [Bailey+ 2015]

- The solar problem is a good illustration of the connections between atomic physics and astrophysics
- Atomic \rightarrow Astro
	- Improved log gf's = well-constrained 1D LTE composition (e.g. 1990's)

Atomic-astrophysics connections **ent gf-values. The very large dispersion noted for works prior to [43] reduces tremendously when using the accurate gf-values of [43]. It also shows that results prior to [43] were in complete disagreement with the**

r iron abundance with improving log of data [Grevesse & Noels 1993] **very accurate gf-values of Oxford [31]. Earlier results are obtained using Evolution of solar iron abundance with improving log gf data [Grevesse & Noels 1993]**

Atomic-astrophysics connections RESEARCH LETTER

- The solar problem is a good illustration of the connections between atomic physics and astrophysics
- Atomic \rightarrow Astro
	- Improved log gf's = well-constrained 1D LTE composition (e.g. 1990's)
- Astro \rightarrow Atomic
	- More realistic 3D/non-LTE models in the 2000's helped motivate a deeper look into theoretical opacities

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The message of this talk

- Rapid progress in developing 3D non-LTE model stellar spectra, with increasing sophistication and accuracy
- Cause/caused by stronger connections between atomic/astrophysics
- Atomic \rightarrow Astro
	- Improved atomic data *improve the models*
	- Reveal *new astrophysics*
- Astro \rightarrow Atomic
	- Use Sun/stars for *complementary tests of atomic data?*

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Imprints of solar system formation

- The solar abundances are reaching precision/accuracy to resolve possibly intrinsic differences with pristine meteorites
- Trend with condensation temperature at ~2 sigma

Sun - meteoritic abundances versus condensation temperature [Asplund+ 2021] $\mathcal{F}_{\mathcal{F}}$ fig. $\mathcal{F}_{\mathcal{F}}$ of the photospheric and $\mathcal{F}_{\mathcal{F}}$ chondritic logarithm-independent of the photospheric logarithm

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- Astro → Atomic - Use Sun/stars for *complementary tests of atomic data?*

Astrophysical tests of atomic data

- Oscillator strengths
	- Examine scatter and trends in line-by-line analyses of standard stars using different data sets

Astrophysical tests of N I oscillator strengths [Li et al. 2023] transition data computed in this work. The left panel also includes results based on the experimental data of Musielok et al. (1995) and Bridges & Wiese (2010), while

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Astrophysical tests of C I oscillator strengths [Li et al. 2021]

Astrophysical tests of atomic data

- Oscillator strengths
	- Examine scatter and trends in line-by-line analyses of standard stars using different data sets
- Broadening parameters
	- Examine detailed line shapes

Validation of hydrogen collisional broadening data [Barklem 2016]

Testing inelastic hydrogen collisions using the O I 777nm [Amarsi+ 2018] iesting inetasuc nyurogen cotusions using the

Astrophysical tests of atomic data $\overline{13}$ \pm 0.0 \pm 0.000 \pm 0.000 \pm 0.000 \pm 0.000 3 8656–8668 7825–7842 8691–8708 16 0.203 16 0.397 19 0.603 20 0.801 9 1.0000 ±0.006 ±0.027 ±0.006 ±0.004 ±0.0005

- Oscillator strengths $\bigcap_{n\in\mathbb{Z}}$ Nordlund (1984, 1985) pioneered the investigation of NLTE line
- Examine scatter and trends in line-by-line analyses of standard stars using different data sets formation of iron in 3D hydrodynamical model atmospheres more - Examine scatter and trends $\mathbf{F}_{\mathbf{f}}$ is the same significant balance and reported significant balance and repor Ine-by-line analyses of stand in the neutral species. In the second paper in the second paper in the second paper. \blacksquare stars using different data se 5225 Å due to a superthermal source function.

East

- Broadening parameters $1.5\,$ D approximation, neglecting horizontal radiative transfer. They are transfer. They are transfer. They are they are they are they are they are the second transfer. They are they are they are they are they are they a
- Examine detailed line shapes Γ_{S} vary strongly with the granulation pattern and the Fe ^I line proper-
- Inelastic collisions $\frac{1}{2}$ dex for the lowest excitence on $\frac{1}{2}$ \blacksquare inelastic collisions of in the \blacksquare
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Astrophysical tests of atomic data 2.2×10^{-10}

- Oscillator strengths
- Broadening parameters
- Inelastic collisions
- More ideas are welcome
	- Increasing potential to use stars as lab benches as 3D non-LTE models continue to improve in sophistication

Error in the predicted interior sound speed [Stasińka+ 2012]

Conclusion

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