Expanded Spectral Atlas of Sirius

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Context and Need

As the brightest star in our night sky, Sirius A (see Figure 1) is used as a standard star for astronomical measurements (Rieke et al. 2023) and has been meticulously observed. The parameters of Sirius have been measured to high precision (see Table 1), and its characteristics provide insight into stellar atmospheres and stellar evolution. However, despite the parameters being well constrained, there is much uncertainty regarding the chemical abundances of Sirius's atmosphere. Abundances of the elements, assuming local thermodynamic equilibrium (LTE), are known at best to 25%, many uncertain by 200% or more (Landstreet 2011).

Over forty years ago, Kurucz & Furenlid (1979) pointed out that LTE stellar atmosphere models were likely a good approximation for Sirius, given the high collision rates associated with its reasonably high surface gravity. These authors created a spectral atlas for Sirius A, comparing a high-resolution spectrum they obtained at Kitt Peak to a synthetic spectrum between 3540 Å and 4400 Å, labeling every line.

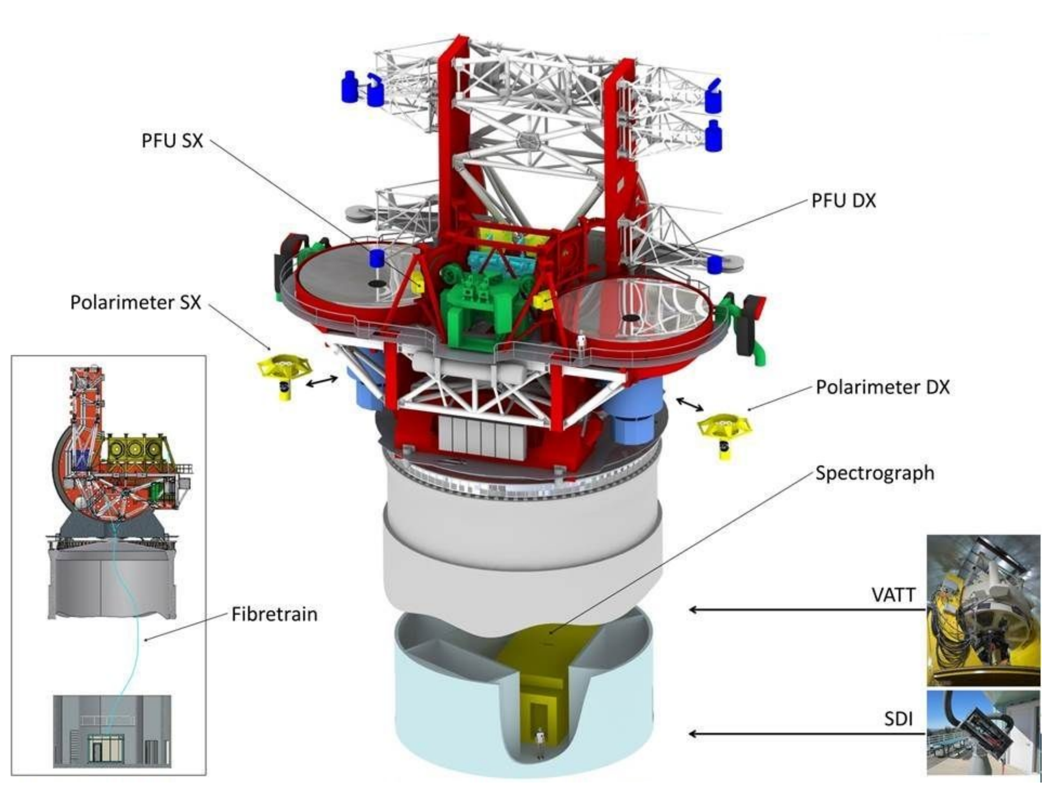

Figure 2: PEPSI spectrograph at the Large Binocular Telescope at Mount Hopkins in Arizona.

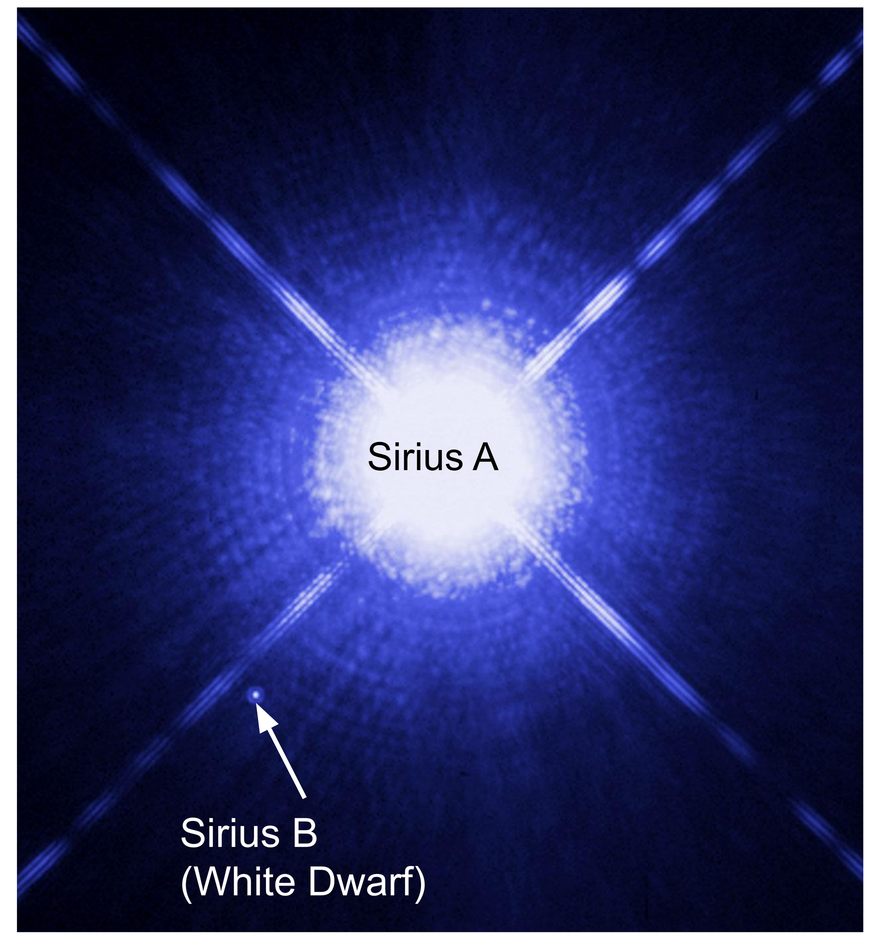

Figure 1: Image of Sirius A and B taken from the Hubble Space Telescope.

Table 1

- ✭ Mass = 2.063±0.023 $M_\odot$ (1%, Bond et al. 2017).
- ✭ Angular diameter = 6.04±0.02 mas (0.3%, Davis et al. 2011)
- ✭ Distance = 2.64±0.01 pc (0.4% van Leeuwen 2007)
- ✭ Radius = 1.713±0.007 $R_\odot$ (0.5%, derived)
- ✭ Surface gravity = 190.5±0.8 m s^{-2} (0.4%, derived)
- ✭ Bolometric flux = 114.1±2.9x10^{-9} W m^{-2} (3%, Davis et al 2011)
- ✭ Effective temperature = 9845±64 K (0.7%, Davis et al. 2011)

Task

Using archival data taken from PEPSI (Potsdam Echelle Polarimetric and Spectroscopic Instrument, Figure 2) and VLT/UVES (Very Large Telescope Ultraviolet and Visual Echelle Spectrograph, Figure 3) in comparison to a normalized non-LTE Phoenix model, we have constructed an atlas running from 3050 Å to 8500 Å and removed the LTE assumption.

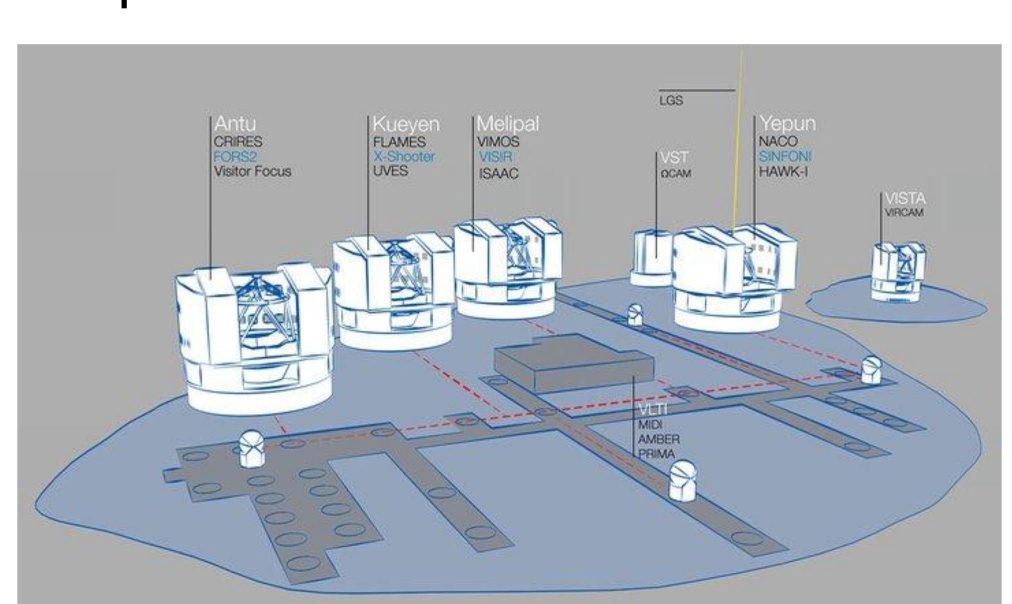

Figure 3: UVES spectrograph on the U2 Telescope of the Very Large Telescope at Paranal Observatory in the Atacama Desert, Chile.

Results

We present here 5 selected panels of the 642 panels in the working draft of our atlas.

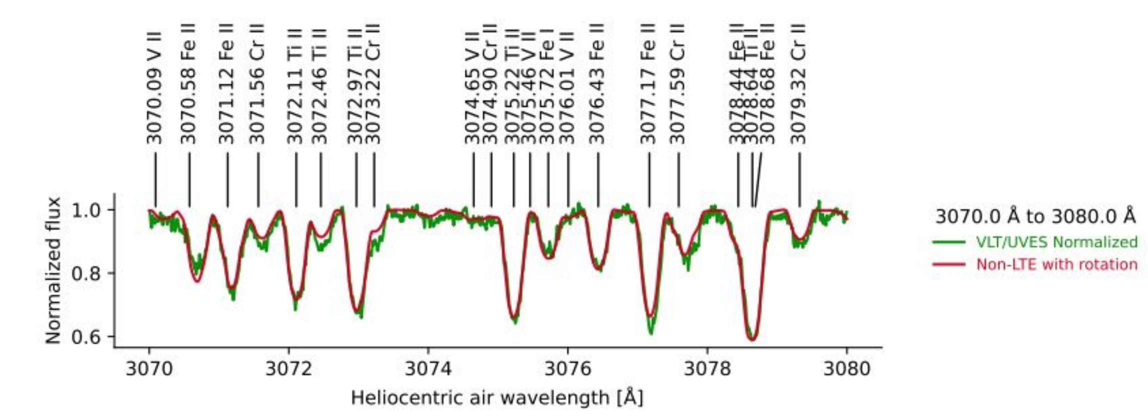

Figure 4: Panel of the VLT/UVES normalized spectrum compared with the non-LTE model between 3070 Å and 3080 Å which shows a good match between the two spectra. These wavelengths are 500 Å shortward of the Kurucz and Furenlid spectral atlas.

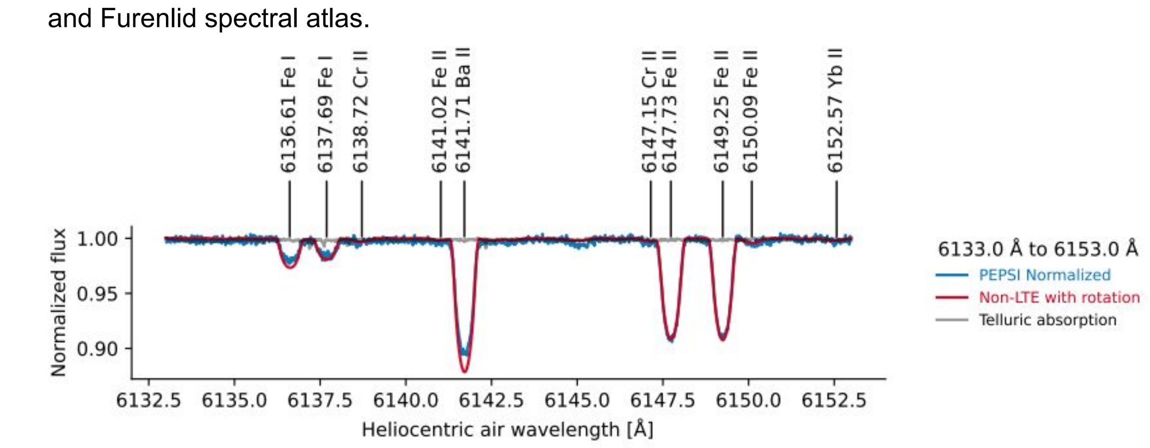

Figure 5: Panel of the PEPSI normalized spectrum compared with the non-LTE model where PEPSI data has higher signal-to-noise than VLT/UVES.

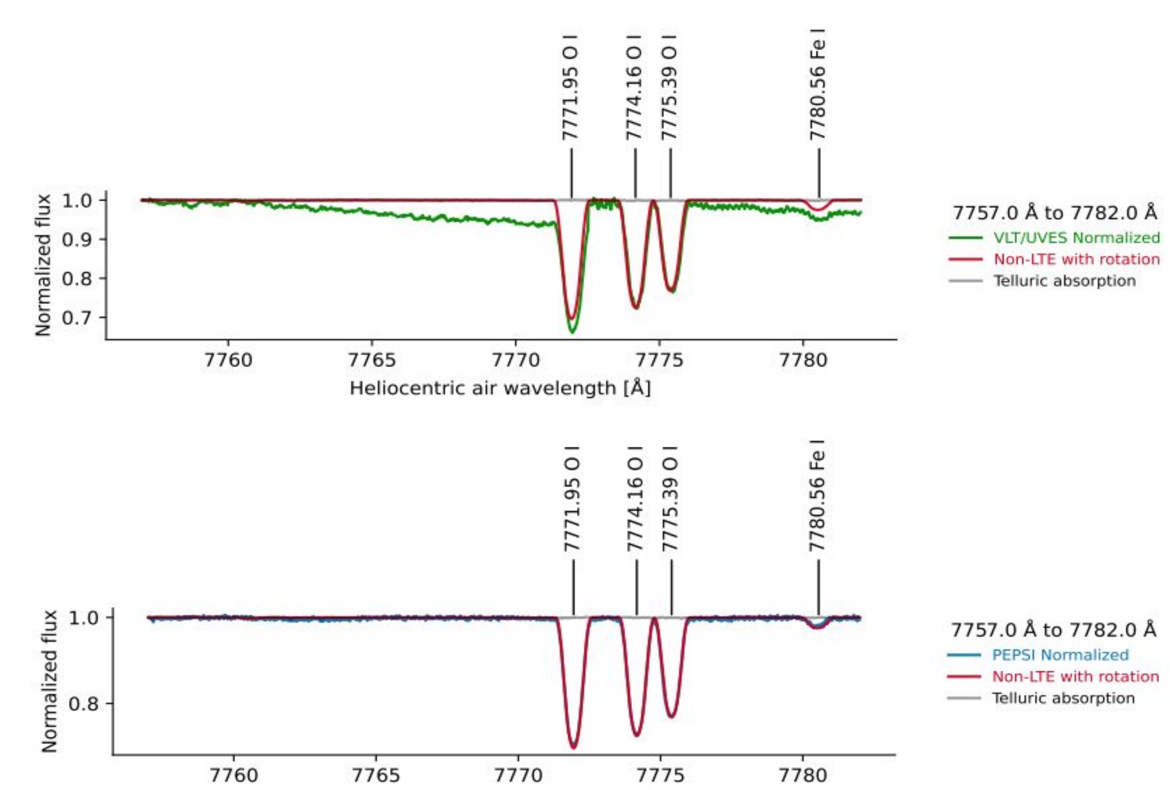

Figure 6: Comparison of VLT/UVES and the PEPSI spectrum compared to our model near 7757 Å and it is clear that PEPSI is a better match, free from systematic error.

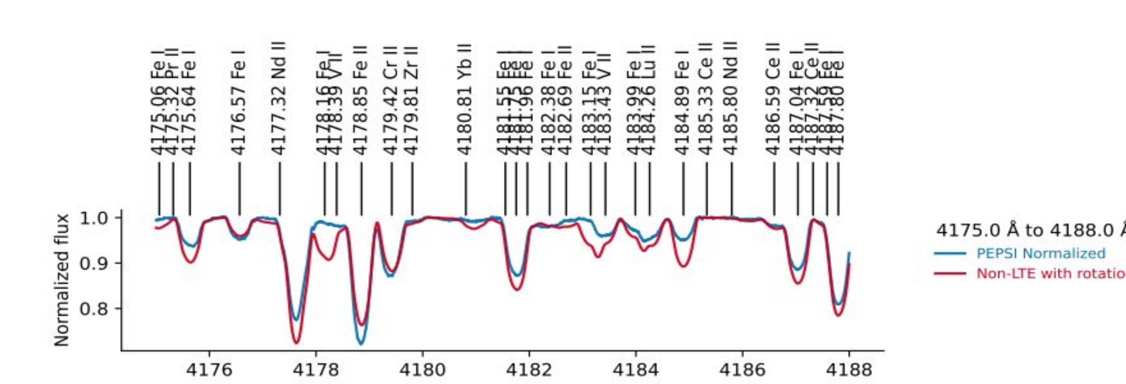

Figure 7: This panel shows shows well-matched and not well-matched lines, e.g. Fe I 4176.57 Å presents a good match, while Fe I 4178.16 Å appears to be present in the model but is missing from the PEPSI data. Other Fe I lines such as 4175.64 Å or 4187.04 Å are also too strong in the model.

Conclusions

Our initial analysis using the VLT/UVES spectrum identified systematic errors in both the data and the model. This influenced our use of another observed spectrum, taken by PEPSI, to help identify errors and choose the best spectrum for each panel. Using both data sets allows a broad wavelength range for the atlas, providing an in-depth analysis between observed data and model predictions.

Perspectives

Our next steps will be to (1) quantify each line mismatch of the model and data, and (2) use the National Institute of Standards and Technology (NIST) database to compare the mismatch to the atomic data quality grade of each absorption line.

References

Sirius A as a photometric standard: see Rieke et al. (2023) in the *Astronomical Journal*, 165, 99.

VLT/UVES spectrum of Sirius: Paranal Observatory Project program, see Bagnulo, S., Jehin, E., Ledoux, C., et al. 2003 in The European Southern Observatory (ESO) *Messenger,* 114, 10

PEPSI spectrum of Sirius: see K. G. Strassmeier, I. Ilyin, and M. Weber (2018) in *Astronomy & Astrophysics* 612, A45

Large Binocular Telescope illustration is from Strassmeier et al. (2015) in *Astronomische Nachrichten*, 336, 324.

Very Large Telescope illustration is from http://www.eso.org/public/archives/images/large/vlt.jpg

The original atlas from R. Kurucz and I. Furenlid (1979) in Sample Spectral Atlas for Sirius Special, Report 387. *Smithsonian Astrophysical Observatory.*

Sirius A orbital parameters from Bond, H. E., et al. (2017) in the *Astrophysical Journal*, 840, 70; Angular diameter, bolometric flux and effective temperature from Davis, J. et al. (2011) in *Publications of the Astronomical Society of Australia*, 28, 58; parallax from van Leeuwen, F. (2007) in *Astronomy & Astrophysics*, 474, 65.

Chemical abundance uncertainties from Landstreet, J. D. (2011) in *Astronomy & Astrophysics,* 528, A132

Model atmospheres were computed using the Phoenix code, see Hauschildt and Baron (1999) in *Journal of Computational and Applied Mathematics,* 109, 41.

Python code development was aided using Jupyter notebooks at **cocalc.com**.