

# The GALAH Survey: Third Data Release

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## ABSTRACT

This is the current draft of the accompanying paper for GALAH Data Release 3. Please feel free to give feedback regarding both the analysis and the manuscript.

**Key words:** Surveys – the Galaxy – methods: observational – methods: data analysis – stars: fundamental parameters – stars: abundances

## 1 INTRODUCTION

## 2 TARGET SELECTION, OBSERVATION, REDUCTION

The selection was based on 2MASS (Skrutskie et al. 2006) magnitudes and due to their brightness, almost all stars of the GALAH observations have well measured 5D information from *Gaia* (Gaia Collaboration et al. 2018; Lindegren et al. 2018). An overview of the astro- and photometric information of the observed spectra can be found in Fig. 1

## 3 DATA ANALYSIS

### 3.1 Analysis flow and changes with respect to DR2

- SME only, no use of *The Cannon* in this DR
- Lay this out and motivate that by a figure, which shows 3 panels in the top for DR2 (Teff-logg, [Fe/H]-[alpha/Fe], [Fe/H]-A(Li)) and DR3 in the bottom
- SME536, including changes as introduced by Piskunov & Valenti (2017), but also with additional differences in the use of SME
- using fundamental relation of surface gravity log g with available, non-spectroscopic information ( $\varpi$  and  $K_S$ )
- Workflow:
  - (i) Estimate stellar parameters ( $T_{\text{eff}}$ , [Fe/H],  $v_{\text{broad}}$ ,  $v_{\text{rad}}$  from spectra, log g via fundamental relation,  $v_{\text{mic}}$  via empirical relation)
  - (ii) Validation of stellar parameters (see Sec.3.2), leading to an adjustment of the estimated atmospheric [Fe/H] (SME.FEH) by adding 0.1 dex<sup>1</sup>
  - (iii) Keep stellar parameters fixed and then estimate A(X) for element X. These can be done combined (write elements for which that was done) or on a line-by-line basis (write elements for which that was done).

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<sup>1</sup> NB: This is not the final [Fe/H] as reported in this data release, but a pseudo iron abundance, estimated from H, Sc, Ti, and Fe lines.

### 3.2 Validation of stellar parameters

To assess the quality of the stellar parameters, we resort to the commonly used comparison samples for accuracy, that is the GBS and the stars with asteroseismic information. For the precision assessment we use the internal uncertainty estimates and repeat observations of the same stars. We calculate the final stellar parameter errors for a given parameter  $X$  via

$$e_{\text{final}}^2(X) = e_{\text{accuracy}}^2(X) + e_{\text{fit}}^2(X) + e_{\text{repeats}}^2(X). \quad (1)$$

We note that  $e_{\text{fit}}^2(X)$  and  $e_{\text{repeats}}^2(X)$  are typically expected to be the same tracer of precision and hence only their maximum value should be used, that is

$$e_{\text{final}}^2(X) = e_{\text{accuracy}}^2(X) + \max(e_{\text{fit}}^2(X) + e_{\text{repeats}}^2(X)). \quad (2)$$

We elaborate on the choice of error combination when we assess the precision of the stellar parameters.

#### 3.2.1 Accuracy of stellar parameters

#### *Gaia* FGK benchmark stars (GBS)

#### IRFM temperatures

#### Stars with asteroseismic information

#### 3.2.2 Precision of stellar parameters

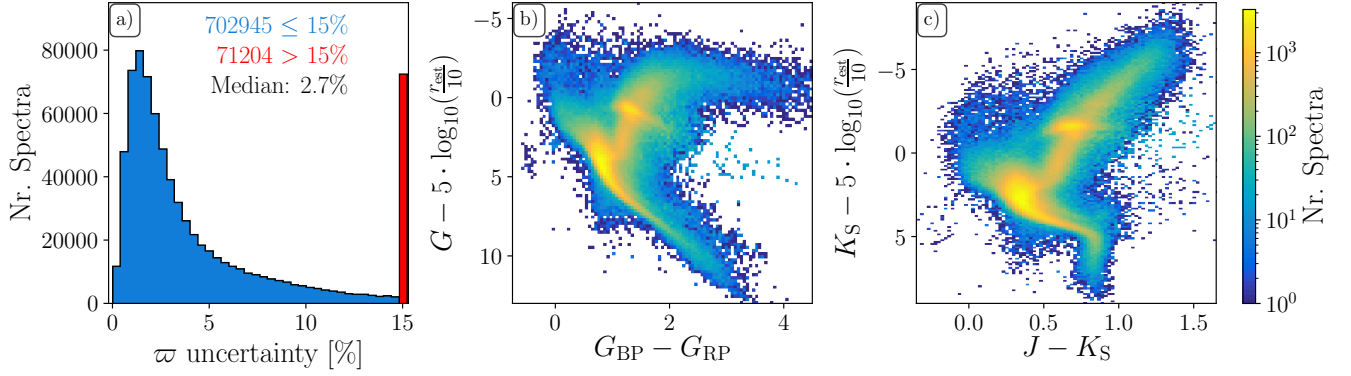
- repeat observations and fitting uncertainties

## 4 VALIDATION OF ELEMENT ABUNDANCES

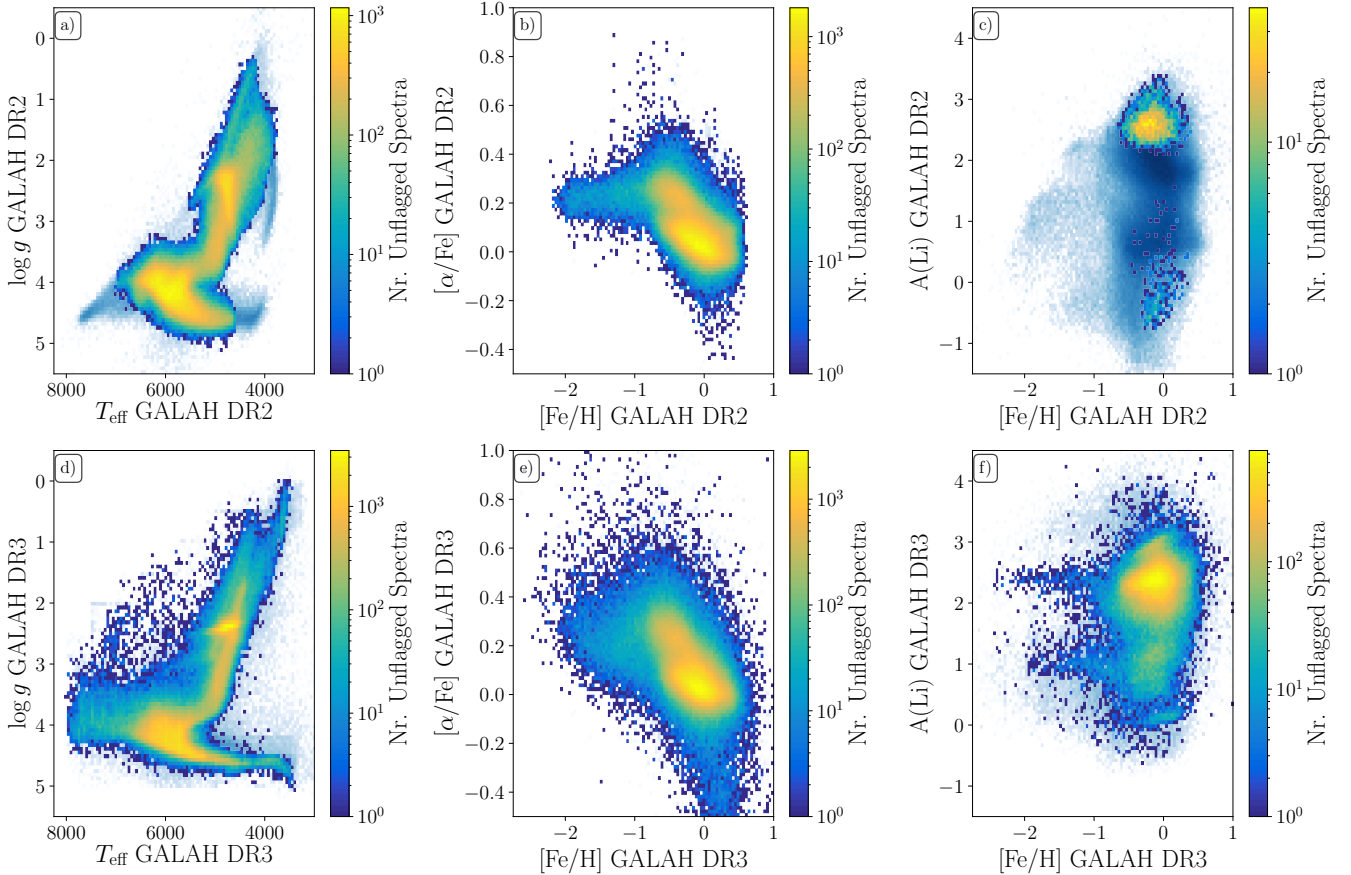
### 4.0.1 Accuracy of element abundances

#### Abundances of the Sun

#### Abundances of Arcturus



**Figure 1.** Overview of astro- and photometric information of the stars observed by GALAH until [SB: February 2019](#). Panel a) shows the unprecedented parallax ( $\varpi$ ) uncertainty provided by *Gaia* DR2 with 702945 (91%) spectra below 15% (blue) and 71204 (9%) spectra with uncertainties above 15% (red, truncated). Panel b) shows a color-magnitude diagram as observed with the optical *Gaia* passbands, whereas panel c) shows a color-magnitude diagram as observed with the infra-red 2MASS passbands. **SB: Note that not all of these stars are included in GALAH DR3.**



**Figure 2.** Comparison of GALAH DR2 (upper panels) and GALAH DR3 (lower panels, this release). Pale blue contours indicate all measurements, whereas the colors as part of the colormaps indicate the unflagged measurements. Left panels show Kiel diagrams, i.e.  $T_{\text{eff}} - \log g$ , for stars of DR2 (a) and DR3 (d). Middle panels show the abundance pattern of iron vs.  $\alpha$ -process elements, i.e.  $[\text{Fe}/\text{H}] - [\alpha/\text{Fe}]$ , for DR2 (b) and DR3 (e). Right panels show the absolute Li abundance as a function of iron abundance, i.e.  $[\text{Fe}/\text{H}] - A(\text{Li})$ , for DR2 (c) and DR3 (f). Note that the stars are not only the overlapping ones, but all measurements of the particular release.

**Abundances of the GBS stars****TBD: Abundances of cluster stars?***4.0.2 Precision of element abundances***Abundances of repeat observations****TBD: Abundances of cluster stars?****4.1 The complexity and importance of flagging (and using them)***4.1.1 Flagging of stellar parameters**4.1.2 Flagging of element abundances*

We expect less trends without the influence of the training set selection or data-model flexibilities, but we still expect trends for several reasons:

- Given the model- and setup-imperfections, excluding  $\log g$  as a free fitting parameter might lead to systematic trends. This can be the case for those stars where the true  $\log g$  of the star and our estimated  $\log g$  differ significantly (e.g. binaries where the (unidentified) second component is contributing to the flux of the system) or the synthetic spectrum with the true  $\log g$  does not match the observation (e.g. due to shortcomings of the 1D model atmospheres and synthesis).
- For stars with more lines, our pipeline will perform worse several ways. Firstly, estimating the continuum will be less reliable. Secondly, we will run into issues of strong blending, where our estimate is limited to how close the synthesis of the blending lines is to the true observation. If for example a star has scaled solar abundances, our estimates of the element abundances will still be good even for blended cases. If the compositions differs, and the line that we want to measure is blended by a line of a significantly over- or under-abundant element (relative to scaled-solar), our measurement might be corrupted. We try to limit this by performing a blending test, but setting the limit on how much blending is still acceptable is both non-trivial but also hard to flag during post-processing.
- Due to time/computation restrictions, we were running several elements in a combined rather than line-by-line basis, which can decrease the precision as outlined in Sec. 3.1, although we have tried to ensure that the abundance zero points of the individual lines were similar for those elements that were run with the combined setup.

*4.1.3 Expect the (un-)expected, but be cautious: Analysis shortcoming or physical correlation?***5 CATALOGS INCLUDED IN THIS RELEASE****5.1 Main catalog**

- (i) Stellar parameters (see Fig. ??)
- (ii) Stellar parameter flags (both warning and flags)
- (iii) Precision uncertainties and final uncertainties for each parameter (including accuracy, precision, and parameter node uncertainties)
- (iv) Combined alpha-abundance (for unflagged measurements), see Fig. ??
- (v) Individual element abundances (including flagged measurements)
- (vi) individual abundance flags

(vii) Precision uncertainties for each abundance

(viii) x-matches with Gaia DR2, Bailer-Jones2018, RUWE, 2MASS, WISE

**5.2 Value-Added-Catalogs**

The third Data Release of GALAH is accompanied by two value-added-catalogs and we explain them in this section. One value-added-catalog includes extended abundance measurement information, another one stellar ages as well as masses and a third one kinematic as well as dynamic information for each star.

*5.2.1 Extended abundance measurement information**5.2.2 Stellar age and mass estimates**5.2.3 Kinematic and dynamic information***6 GALAH DR3 IN CONTEXT****6.1 Galactic archaeology on a global scale****6.2 Chemodynamical evolution**

Combining chemistry, dynamics, and ages of stars

- plot Galactic  $v_R$  vs.  $v_\phi$  (Belokurov) - plot Toomre diagram - plot actions - plot Vasiliev (2019) overview of  $J_i$

**7 CONCLUSIONS****ACKNOWLEDGEMENTS**

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## REFERENCES

- Astropy Collaboration et al., 2013, *A&A*, **558**, A33
- Bard A., Kock M., 1994, *Astron. and Astrophys.*, **282**, 1014
- Bard A., Kock A., Kock M., 1991, *Astron. and Astrophys.*, **248**, 315
- Biemont E., Grevesse N., Hannaford P., Lowe R. M., 1981, *ApJ*, **248**, 867
- Blackwell-Whitehead R. J., Lundberg H., Nave G., Pickering J. C., Jones H. R. A., Lyubchik Y., Pavlenko Y. V., Viti S., 2006, *Monthly Notices Roy. Astron. Soc.*, **373**, 1603
- Blackwell D. E., Ibbetson P. A., Petford A. D., Shallis M. J., 1979, *MNRAS*, **186**, 633
- Blackwell D. E., Petford A. D., Shallis M. J., Simmons G. J., 1982a, *MNRAS*, **199**, 43
- Blackwell D. E., Petford A. D., Simmons G. J., 1982b, *MNRAS*, **201**, 595
- Blackwell D. E., Menon S. L. R., Petford A. D., 1983, *MNRAS*, **204**, 883
- Blackwell D. E., Booth A. J., Menon S. L. R., Petford A. D., 1986, *MNRAS*, **220**, 289
- Bovy J., 2015, *ApJS*, **216**, 29
- Cardon B. L., Smith P. L., Scalo J. M., Testerman L., Whaling W., 1982, *ApJ*, **260**, 395
- Carlsson J., Stenlund L., Svanberg S., 1989, *Zeitschrift für Physik D Atoms Molecules Clusters*, **11**, 287
- Chang T. N., Tang X., 1990, *J. Quant. Spectrosc. Radiative Transfer*, **43**, 207
- Corliss C. H., Bozman W. R., 1962, Experimental transition probabilities for spectral lines of seventy elements; derived from the NBS Tables of spectral-line intensities. NBS Monograph Vol. 53, US Government Printing Office
- Davidson M. D., Snoek L. C., Volten H., Doenszelmann A., 1992, *A&A*, **255**, 457
- Den Hartog E. A., Lawler J. E., Sneden C., Cowan J. J., 2003, *Astrophys. J. Suppl. Ser.*, **148**, 543
- Den Hartog E. A., Lawler J. E., Sobek J. S., Sneden C., Cowan J. J., 2011, *ApJS*, **194**, 35
- Den Hartog E. A., Ruffoni M. P., Lawler J. E., Pickering J. C., Lind K., Brewer N. R., 2014a, *ApJS*, **215**, 23
- Den Hartog E. A., Ruffoni M. P., Lawler J. E., Pickering J. C., Lind K., Brewer N. R., 2014b, *ApJS*, **215**, 23
- Froese Fischer C., Tachiev G., 2012, Multiconfiguration Hartree-Fock and Multiconfiguration Dirac-Hartree-Fock Collection, Version 2
- Fuhr J. R., Martin G. A., Wiese W. L., 1988, *Journal of Physical and Chemical Reference Data*, Volume 17, Suppl. 4. New York: American Institute of Physics (AIP) and American Chemical Society, 1988, **17**
- Gaia Collaboration et al., 2018, *A&A*, **616**, A1
- Garz T., 1973, *A&A*, **26**, 471
- Grevesse N., Blackwell D. E., Petford A. D., 1989, *A&A*, **208**, 157
- Grevesse N., Scott P., Asplund M., Sauval A. J., 2015, *A&A*, **573**, A27
- Hibbert A., Biemont E., Godefroid M., Vaecck N., 1993, *A&AS*, **99**, 179
- Hunter J. D., 2007, *Computing In Science & Engineering*, **9**, 90
- Kelleher D. E., Podobedova L. I., 2008, *Journal of Physical and Chemical Reference Data*, **37**, 709
- Kock M., Richter J., 1968, *Z. Astrophys.*, **69**, 180
- Kurucz R. L., 2006, Robert L. Kurucz on-line database of observed and predicted atomic transitions
- Kurucz R. L., 2007, Robert L. Kurucz on-line database of observed and predicted atomic transitions
- Kurucz R. L., 2008, Robert L. Kurucz on-line database of observed and predicted atomic transitions
- Kurucz R. L., 2009, Robert L. Kurucz on-line database of observed and predicted atomic transitions
- Kurucz R. L., 2010, Robert L. Kurucz on-line database of observed and predicted atomic transitions
- Kurucz R. L., 2013, Robert L. Kurucz on-line database of observed and predicted atomic transitions
- Kurucz R. L., 2014, Robert L. Kurucz on-line database of observed and predicted atomic transitions
- Lawler J. E., Dakin J. T., 1989, *Journal of the Optical Society of America B Optical Physics*, **6**, 1457
- Lawler J. E., Bonvallet G., Sneden C., 2001a, *Astrophys. J.*, **556**, 452
- Lawler J. E., Wickliffe M. E., den Hartog E. A., Sneden C., 2001b, *Astrophys. J.*, **563**, 1075
- Lawler J. E., Den Hartog E. A., Sneden C., Cowan J. J., 2006, *Astrophys. J. Suppl. Ser.*, **162**, 227
- Lawler J. E., Sneden C., Cowan J. J., Ivans I. I., Den Hartog E. A., 2009, *Astrophys. J. Suppl. Ser.*, **182**, 51
- Lawler J. E., Guzman A., Wood M. P., Sneden C., Cowan J. J., 2013, *ApJS*, **205**, 11
- Lawler J. E., Wood M. P., Den Hartog E. A., Feigenson T., Sneden C., Cowan J. J., 2014, *ApJS*, **215**, 20
- Lawler J. E., Sneden C., Cowan J. J., 2015, *ApJS*, **220**, 13
- Lindgren L., et al., 2018, preprint, ([arXiv:1804.09366](https://arxiv.org/abs/1804.09366))
- Martin G., Fuhr J., Wiese W., 1988, *J. Phys. Chem. Ref. Data Suppl.*, **17**
- May M., Richter J., Wichelmann J., 1974, *A&AS*, **18**, 405
- Mckinney W., 2011, in *Python High Performance Science Computer*.
- Meggers W. F., Corliss C. H., Scribner B. F., 1975, *Tables of spectral-line intensities. Part I, II\_- arranged by elements.. NBS*
- Meléndez J., Barbay B., 2009, *A&A*, **497**, 611
- Miszalski B., Shorridge K., Saunders W., Parker Q. A., Croom S. M., 2006, *MNRAS*, **371**, 1537
- Nahar S. N., 1993, *Phys. Scr.*, **48**, 297
- Nitz D. E., Wickliffe M. E., Lawler J. E., 1998, *Astrophys. J. Suppl. Ser.*, **117**, 313
- Nitz D. E., Kunau A. E., Wilson K. L., Lentz L. R., 1999, *ApJS*, **122**, 557
- O'Brian T. R., Wickliffe M. E., Lawler J. E., Whaling W., Brault J. W., 1991, *Journal of the Optical Society of America B Optical Physics*, **8**, 1185
- O'brian T. R., Lawler J. E., 1991, *Phys. Rev. A*, **44**, 7134
- Palmeri P., Quinet P., Wyart J., Biémont E., 2000, *Physica Scripta*, **61**, 323
- Palmeri P., Quinet P., Lundberg H., Engström L., Nilsson H., Hartman H., 2017, *MNRAS*, **471**, 532
- Pérez F., Granger B. E., 2007, *Computing in Science and Engineering*, **9**, 21
- Piskunov N., Valenti J. A., 2017, *A&A*, **597**, A16
- Raassen A. J. J., Uylings P. H. M., 1998, *A&A*, **340**, 300
- Ralchenko Y., Kramida A., Reader J., NIST ASD Team 2010, *NIST Atomic Spectra Database (ver. 4.0.0)*, [Online].
- Ruffoni M. P., Den Hartog E. A., Lawler J. E., Brewer N. R., Lind K., Nave G., Pickering J. C., 2014, *MNRAS*, **441**, 3127
- Skrutskie M. F., et al., 2006, *The Astronomical Journal*, **131**, 1163
- Smith G., 1988, *Journal of Physics B Atomic Molecular Physics*, **21**, 2827
- Smith G., Raggett D. S. J., 1981, *Journal of Physics B Atomic Molecular Physics*, **14**, 4015
- Sobek J. S., Lawler J. E., Sneden C., 2007, *Astrophys. J.*, **667**, 1267
- Taylor M. B., 2005, in Shopbell P., Britton M., Ebert R., eds, *Astronomical Society of the Pacific Conference Series Vol. 347, Astronomical Data Analysis Software and Systems XIV*. p. 29
- The Astropy Collaboration et al., 2018, preprint, ([arXiv:1801.02634](https://arxiv.org/abs/1801.02634))
- Tody D., 1986, in Crawford D. L., ed., *Proc. SPIE Vol. 627, Instrumentation in astronomy VI*. p. 733, [doi:10.1117/12.968154](https://doi.org/10.1117/12.968154)
- Tody D., 1993, in Hanisch R. J., Brissenden R. J. V., Barnes J., eds, *Astronomical Society of the Pacific Conference Series Vol. 52, Astronomical Data Analysis Software and Systems II*. p. 173
- Trubko R., Gregoire M. D., Holmgren W. F., Cronin A. D., 2017, *Phys. Rev. A*, **95**, 052507
- Vaeck N., Godefroid M., Hansen J. E., 1988, *Phys. Rev. A*, **38**, 2830
- Vasiliev E., 2019, *MNRAS*, **484**, 2832

- Walt S. v. d., Colbert S. C., Varoquaux G., 2011, [Computing in Science and Engg.](#), 13, 22
- Wickliffe M. E., Salih S., Lawler J. E., 1994, [J. Quant. Spectrosc. Radiative Transfer](#), 51, 545
- Wood M. P., Lawler J. E., Sneden C., Cowan J. J., 2013, [ApJS](#), 208, 27
- Wood M. P., Lawler J. E., Sneden C., Cowan J. J., 2014, [ApJS](#), 211, 20
- Yan Z.-C., Tambasco M., Drake G. W. F., 1998, [Phys. Rev. A](#), 57, 1652

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## APPENDIX A: LINELIST

This paper has been typeset from a  $\text{\LaTeX}$  file prepared by the author.



**Table A1.** Selected lines for the elemental abundance analysis.

Elem.	Ion	Wavelength [Å]	LEP [eV]	log( <i>gf</i> )	Reference	Line mask [Å]	Segment mask [Å]
Li	1	6707.7635	0.00000	-0.00200000	1998PhRvA...57.1652Y	6707.3000-6708.3000	6705.76-6709.76
Li	1	6707.9145	0.00000	-0.303000	1998PhRvA...57.1652Y	6707.3000-6708.3000	6705.76-6709.76
Li	1	6707.9215	0.00000	-0.00200000	1998PhRvA...57.1652Y	6707.3000-6708.3000	6705.76-6709.76
Li	1	6708.0725	0.00000	-0.303000	1998PhRvA...57.1652Y	6707.3000-6708.3000	6705.76-6709.76
C	1	6587.6100	8.53700	-1.02100	1993A&AS...99..179H	6587.2610-6587.9860	6585.61-6589.61
O	1	7771.9440	9.14600	0.369000	NIST	7771.3590-7772.5090	7769.50-7777.50
O	1	7774.1660	9.14600	0.223000	NIST	7773.5220-7774.7820	7769.50-7777.50
O	1	7775.3880	9.14600	0.00200000	NIST	7774.9120-7775.9620	7769.50-7777.50
Na	1	5682.6333	2.10200	-0.706000	GESMCHF	5682.5170-5682.9970	5680.63-5691.20
Na	1	5688.2050	2.10400	-0.404000	GESMCHF	5687.9170-5688.3920	5680.63-5691.20
Mg	1	5711.0880	4.34600	-1.72400	1990JQSRT...43..207C	5710.7570-5711.4280	5710.00-5713.09
Al	1	6696.0230	3.14300	-1.56900	2008JPCRD...37..709K	6695.7780-6696.1730	6695.00-6699.87
Al	1	6698.6730	3.14300	-1.87000	2008JPCRD...37..709K	6698.3920-6698.8950	6695.00-6699.87
Al	1	7835.3090	4.02200	-0.689000	2008JPCRD...37..709K	7834.8840-7835.5720	7834.00-7837.50
Al	1	7836.1340	4.02200	-0.534000	2008JPCRD...37..709K	7835.8130-7836.4310	7834.00-7837.50
Al	1	7836.1340	4.02200	-1.83400	2008JPCRD...37..709K	7835.8130-7836.4310	7834.00-7837.50
Si	1	5684.4840	4.95400	-1.55300	GARZ BL	5684.1840-5684.7840	5683.00-5686.00
Si	1	5690.4250	4.93000	-1.77300	GARZ BL	5690.1800-5690.6830	5688.43-5692.43
Si	1	5701.1040	4.93000	-1.95300	GARZ BL	5700.9290-5701.2860	5699.70-5702.00
Si	1	5772.0272	5.61400	-3.10700	K07	5771.8460-5772.4460	5771.15-5773.15
Si	1	5772.1460	5.08200	-1.65300	GARZ BL	5771.8460-5772.4460	5771.15-5773.15
Si	1	5793.0726	4.93000	-1.96300	GARZ BL	5792.7190-5793.3930	5791.07-5794.70
Si	1	6721.2732	5.96400	-5.27200	K07	6721.2000-6722.3000	6718.45-6723.85
Si	1	6721.8481	5.86300	-1.06200	1993PhyS...48..297N	6721.2000-6722.3000	6718.45-6723.85
Si	1	7680.2660	5.86300	-0.590000	GARZ BL	7679.9440-7680.6680	7678.27-7682.27
K	1	7698.9643	0.00000	-0.178000	2017PhRvA...95e2507T	7698.5730-7699.2960	7696.96-7700.96
...	...	...	...	...	...	...	...

References: 1982ApJ...260..395C: [Cardon et al. \(1982\)](#), 1983MNRAS.204..883B|1989A&A...208..157G: [Blackwell et al. \(1983\)](#); [Grevesse et al. \(1989\)](#), 1990JQSRT...43..207C: [Chang & Tang \(1990\)](#), 1992A&A...255..457D: [Davidson et al. \(1992\)](#), 1993A&AS...99..179H: [Hibbert et al. \(1993\)](#), 1993PhyS...48..297N: [Nahar \(1993\)](#), 1998PhRvA...57.1652Y: [Yan et al. \(1998\)](#), 1999ApJS...122..557N: [Nitz et al. \(1999\)](#), 2008JPCRD...37..709K: [Kelleher & Podobedova \(2008\)](#), 2009A&A...497..611M: [Meléndez & Barbuy \(2009\)](#), 2009A&A...497..611M:solar-gf: [Meléndez & Barbuy \(2009\)](#), 2014ApJS...211...20W: [Wood et al. \(2014\)](#), 2014ApJS...215...20L: [Lawler et al. \(2014\)](#), 2014ApJS...215...23D: [Den Hartog et al. \(2014a\)](#), 2014MNRAS.441.3127R: [Ruffoni et al. \(2014\)](#), 2015ApJS...220...13L: [Lawler et al. \(2015\)](#), 2015ApJS...220...13L\_1982ApJ...260..395C: [Lawler et al. \(2015\)](#); [Cardon et al. \(1982\)](#), 2017MNRAS.471..532P: [Palmeri et al. \(2017\)](#), 2017PhRvA...95e2507T: [Trubko et al. \(2017\)](#), BGHL: [Biemont et al. \(1981\)](#), BIPS: [Blackwell et al. \(1979\)](#), BK: [Bard & Kock \(1994\)](#), BK+BWL: [Bard & Kock \(1994\)](#); [O'Brian et al. \(1991\)](#), BK+GESB82d+BWL: [Bard & Kock \(1994\)](#); [Blackwell et al. \(1982b\)](#); [O'Brian et al. \(1991\)](#), BKK: [Bard et al. \(1991\)](#), BKK+GESB82c+BWL: [Bard et al. \(1991\)](#); [Blackwell et al. \(1982a\)](#); [O'Brian et al. \(1991\)](#), BLNP: [Blackwell-Whitehead et al. \(2006\)](#), BWL: [O'Brian et al. \(1991\)](#), BWL+2014MNRAS.441.3127R: [O'Brian et al. \(1991\)](#); [Ruffoni et al. \(2014\)](#), BWL+GESHRL14: [O'Brian et al. \(1991\)](#); [Den Hartog et al. \(2014b\)](#), CB: [Corliss & Bozman \(1962\)](#), DLSSC: [Den Hartog et al. \(2011\)](#), FMW: [Fuhr et al. \(1988\)](#), GARZ|BL: [Garz \(1973\)](#); [O'brian & Lawler \(1991\)](#), GESB82c+BWL: [Blackwell et al. \(1982a\)](#); [O'Brian et al. \(1991\)](#), GESB86: [Blackwell et al. \(1986\)](#), GESB86+BWL: [Blackwell et al. \(1986\)](#); [O'Brian et al. \(1991\)](#), GESMCHF: [Froese Fischer & Tachiev \(2012\)](#), Grevesse2015: [Grevesse et al. \(2015\)](#), HLSC: [Den Hartog et al. \(2003\)](#), K06: [Kurucz \(2006\)](#), K07: [Kurucz \(2007\)](#), K08: [Kurucz \(2008\)](#), K09: [Kurucz \(2009\)](#), K10: [Kurucz \(2010\)](#), K13: [Kurucz \(2013\)](#), K14: [Kurucz \(2014\)](#), KL-astro: astrophysical, KR|1989ZPhyD...11..287C: [Kock & Richter \(1968\)](#); [Carlsson et al. \(1989\)](#), LBS: [Lawler et al. \(2001a\)](#), LD: [Lawler & Dakin \(1989\)](#), LD-HS: [Lawler et al. \(2006\)](#), LGWSC: [Lawler et al. \(2013\)](#), LSCI: [Lawler et al. \(2009\)](#), LWHS: [Lawler et al. \(2001b\)](#), MA-astro: astrophysical, MC: [Meggers et al. \(1975\)](#), MFW: [Martin et al. \(1988\)](#), MRW: [May et al. \(1974\)](#), NIST: [Ralchenko et al. \(2010\)](#), NWL: [Nitz et al. \(1998\)](#), PQWB: [Palmeri et al. \(2000\)](#), RU: [Raassen & Uylings \(1998\)](#), S: [Smith \(1988\)](#), SLS: [Sobeck et al. \(2007\)](#), SR: [Smith & Raggett \(1981\)](#), VGH: [Vaeck et al. \(1988\)](#), WLSC: [Wood et al. \(2013\)](#), WSL: [Wickliffe et al. \(1994\)](#).