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Lithium Detection in Red Supergiant Stars of the Perseus Complex

C. Fanelli[1,2], L. Origlia[2], A. Mucciarelli[1,2], N. Sanna[3], E. Oliva[3], and E. Dalessandro[2]
[1] Dipartimento di Fisica e Astronomia, Universitá degli Studi di Bologna, Via Gobetti 93/2, I-40129 Bologna, Italy; cristiano.fanelli3@unibo.it
[2] INAF-Osservatorio di Astrofisica e Scienza dello Spazio, Via Gobetti 93/3, I-40129 Bologna, Italy
[3] INAF-Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, I-50125 Firenze, Italy
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Abstract

We present the first systematic study of lithium abundance in a chemically homogeneous sample of 27 red supergiants (RSGs) in the young Perseus complex. For these stars, accurate stellar parameters and detailed chemical abundances of iron and iron peak, CNO, alpha, light, and neutron capture elements have already been obtained by means of high-resolution optical and near-infrared spectroscopy. The observed RSGs have half-solar metallicity, 10–30 Myr ages, bolometric luminosities in the 10^4–10^5 $L_\odot$ range, and likely mass progenitors in the 9–14 $M_\odot$ range. We detected the optical Li I doublet in eight out of the 27 observed K- and M-type RSGs, finding relatively low A(Li) < 1.0 dex abundances, while for the remaining 19 RSGs upper limits of A(Li) < –0.2 dex have been set. Warmer and less luminous (i.e., likely less massive) as well as less mixed (i.e., with lower [C/N] and ^{12}C/^{13}C depletion) RSGs with Li detection show somewhat higher Li abundances. In order to explain the Li detection in ∼30% of the observed RSGs, we speculate that some stochasticity should be at work, in a scenario where the Li was not completely destroyed in the convective atmospheres and/or a secondary production took place during the post-main-sequence evolution.

Unified Astronomy Thesaurus concepts: Stellar abundances (1577); Spectroscopy (1558); Red supergiant stars (1375)

1. Introduction

Lithium is a key chemical element for constraining the primordial nucleosynthesis in the universe. Cyburt et al. (2008) obtained a primordial Li abundance A(Li) = 2.72 dex from the theory of big bang nucleosynthesis and the baryon density of WMAP (Dunkley et al. 2009).

In stellar atmospheres, lithium is detectable only in stars cooler than ∼7000 K. Since the first studies of metal-poor Population II stars by Spite & Spite (1982), halo star values of A(Li) ≈ 2.2 have routinely been measured (see, e.g., Charbonnel & Primas 2005, and references therein). In young stars of relatively low mass and at solar metallicity, a lithium abundance A(Li) = 3.2 dex has been measured (see, e.g., Randich 2010; Balachandran et al. 2011) and predicted by most recent chemical evolution models (Grisoni et al. 2019), and this is in good agreement with the meteoritic solar abundance (Grevesse & Sauval 1998; Asplund et al. 2009).

Li detection in massive stars is very rare. Indeed, massive main-sequence (MS) stars are too hot for Li detection, and more evolved supergiants can suffer significant (if not total) Li disruption, due to the development of a convective envelope and the mixing processes. Some early studies of lithium in yellow and K-type supergiants, based on photographic plates (see, e.g., Warren 1973, and references therein), provided upper limits to A(Li) of 1.5–2.0 dex. Gahm & Hultqvist (1976) detected the λλ6708 doublet absorption in S Per, an M4 red supergiant (RSG) of the Perseus complex. More recently, Li abundances A(Li) = 1.3–1.5 have been measured by Lyubimkov et al. (2012) in the two relatively high-mass yellow supergiants, namely HR461 (SpT = KOI) and HR8313 (SpT = G5I), with about solar metallicity. Claims of some Li detection in RSGs of the Perseus complex (with masses between 9 and 10 $M_\odot$) have been made by Negueruela et al. (2020), but no measurements have been published so far.

The young Perseus complex at a Galactocentric distance of about 10 kpc hosts a number of star clusters and associations with ages <100 Myr. The reddening toward the Perseus complex is not too severe ($E(B-V) \approx 0.8$), at variance with other regions of recent star formation in the Galaxy, thus offering a unique opportunity to characterize its stellar content using the full optical and near-infrared (NIR) spectral range.

We performed a simultaneous combined optical and NIR spectroscopic screening at high resolution of the young stellar populations in the Perseus complex, as part of the large program titled SPA—Stellar Population Astrophysics: the detailed, age-resolved chemistry of the Milky Way disk (PI: L. Origlia), at the Telescopio Nazionale Galileo, which aims at measuring detailed chemical abundances and radial velocities of the luminous stellar populations of the the Milky Way thin disk and its associated star clusters (Origlia et al. 2019), We observed 84 luminous blue/yellow and red supergiant stars, for which Gaia EDR3 (Gaia Collaboration et al. 2021) distances and proper motions are available.

A first comprehensive study of the stellar kinematics and spectrophotometric properties in the area surrounding h and χ per double stellar cluster has been presented in Dalessandro et al. (2021). We found that the region is populated by seven comoving clusters, defining a complex structure that we named LISCA I, with kinematic and structural properties consistent with the ongoing formation of a massive cluster (some 10^5 $M_\odot$) through hierarchical assembly.

A detailed chemical study of the 27 RSGs of K and M spectral types in our sample has been recently presented in Fanelli et al. (2022), taking advantage of the several hundreds of atomic and molecular lines available in their high-resolution

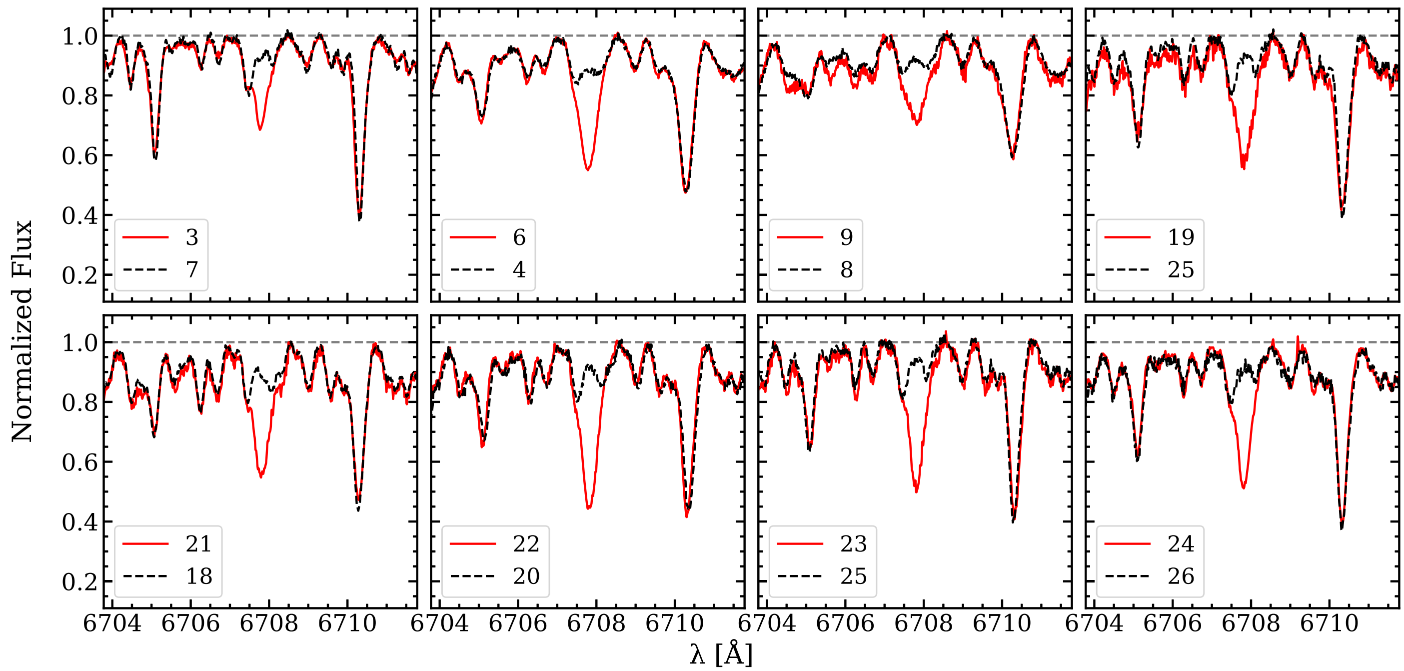

Figure 1. HARPS-N high-resolution spectra around the Li I doublet at 6707.8 Å for the eight RSGs where Li has been detected (red lines), and for corresponding RSGs with similar stellar parameters but without Li (black dashed lines), for comparison. The star IDs from Fanelli et al. (2022) are marked in the bottom left corner of each panel.

optical and NIR spectra, which allow the derivation of reliable stellar parameters and abundances of many different metals, namely iron, iron peak, CNO, alpha, and other light as well as neutron-capture elements. For the accurate stellar parameters of these RSGs, homogeneous half-solar metallicity and about solar-scaled abundances for most of the measured metals have been inferred. Some [C/N] and $^{12}C/^{13}C$ depletion, likely due to mixing processes during the post-MS evolution, has been also measured.

This paper presents the first systematic study of lithium in the atmosphere of such a chemically homogeneous sample of RSGs of K and M spectral types, with progenitor masses in the 9–14 $M_\odot$ range.

2. Lithium Detection and Abundances

We used the HARPS-N spectra of the observed RSGs and we analyzed the region around the $\lambda\lambda$6708 Li I resonance doublet. As detailed in Fanelli et al. (2022), HARPS-N spectra were reduced by the instrument Data Reduction Software pipeline and they were normalized using the code RASSINE (Cretignier et al. 2020). We used the LTE radiative transfer code TURBOSPECTRUM (Alvarez & Plez 1998; Plez 2012) with MARCS model atmospheres (Gustafsson et al. 2008) to model the Li I doublet and spectral synthesis and derive its abundance. Indeed, TiO contamination can be moderate to severe in the optical spectra of RSGs, and we took into account that effect by computing synthetic spectra including TiO transitions, thanks to the most recently updated molecular data from the website of B. Plez.[4] In addition, the Li I doublet can also be partially blended with the lines of CN at 6707.8 Å, Ce II at 6708.1 Å, V I at 6708.11 Å, and Fe I at 6708.28 Å. For these elements, we have estimated accurate abundances in Fanelli et al. (2022), hence we could model their blending contribution quite precisely and verify whether there is an absorption excess likely due to Li in the observed spectra. If such an excess is larger than the blending absorption, we consider it to be an Li detection, otherwise we consider it to be an upper limit. We safely detected lithium in eight out of the 27 observed RSGs. Figure 1 shows the high-resolution HARPS-N spectra around 6708 Å for the eight RSGs with clear Li detection and, for comparison, those of an RSG with similar stellar parameters but without Li.

The inferred Li LTE abundances and corresponding errors are reported in Table 1, together with the stellar parameters and Fe, CNO, $^{12}C/^{13}C$, Na, Mg, and Al abundances from Fanelli et al. (2022). We estimated A(Li) between −0.1 and 0.9 dex in the case of Li detection, and upper limits below −0.2 dex.

Since this Li I doublet is known to suffer from NLTE, we used the computations of Lind et al. (2009) for late-type stars and, by extrapolating them to the stellar parameters and metallicity of the RSGs in Perseus, we estimated positive NLTE corrections of 0.5 ± 0.1 dex. Both the LTE and NLTE abundances are significantly lower (by about two orders of magnitude) than the expected initial value of A(Li) $\approx$ 2.9 at the Perseus half-solar metallicity (Grisoni et al. 2019).

For the remaining 19 RSGs in the sample of Fanelli et al. (2022), no reliable detection could be obtained, and upper limits to the Li abundance of A(Li) $<$ −0.2 dex have been obtained.

Figure 2 shows the inferred Li abundance as a function of the stellar luminosity and effective temperature and of the [C/N], $^{12}C/^{13}C$, [O/Fe], [Na/Fe], [Mg/Fe], and [Al/Fe] abundance ratios. For the subsample of eight RSGs with Li detection, there is evidence of some anticorrelation between the Li abundance and the stellar luminosity and of correlation with the effective temperature, suggesting that Li is more abundant in less luminous and warmer (i.e likely less massive) stars. There is also evidence of some anticorrelation between the Li abundance and the [C/N] and $^{12}C/^{13}C$ ratios, which probe

[4] https://www.lupm.in2p3.fr/users/plez/

Table 1
Stellar Parameters and LTE Chemical Abundances for the Eight RSGs in the Perseus Complex with Detected Lithium

#	Star	$T_{\rm eff}$ (K)	log(g) (dex)	ξ (km s^{-1})	$L_{\rm bol}$[a] $\log(L/L_\odot)$	[Fe/H] (dex)	A(C) (dex)	A(N) (dex)	^{12}C/^{13}C (dex)	A(O) (dex)	A(Na) (dex)	A(Mg) (dex)	A(Al) (dex)	A(Li) (dex)	ϵ(Li) (dex)
3	V439 Per	3690	0.25	3.40	4.44	−0.27	7.98	8.04	8	8.32	6.19	7.31	6.12	0.38	0.09
6	BD+57 540	4125	0.70	2.10	4.18	−0.33	8.18	7.64	29	8.46	6.02	7.30	6.25	0.71	0.15
9	T Per	3594	0.01	3.30	4.63	−0.31	7.99	8.00	7	8.41	6.18	7.22	6.30	−0.11	0.10
19	WX Cas	3787	0.23	3.00	4.50	−0.30	7.97	7.80	12	8.39	6.10	7.27	6.16	0.29	0.09
21	IRAS01530 + 6149	3793	0.25	2.60	4.49	−0.30	8.03	7.86	13	8.56	6.23	7.31	6.25	0.40	0.09
22	BD+61 369	3869	0.53	2.60	4.24	−0.26	8.04	7.94	17	8.49	6.29	7.30	6.26	0.81	0.13
23	DO 24697	3896	0.50	2.40	4.29	−0.24	8.07	7.89	19	8.51	6.26	7.34	6.26	0.68	0.17
24	BD+60 287	4009	0.79	2.50	4.04	−0.28	8.10	7.83	21	8.56	6.34	7.29	6.32	0.81	0.13

Notes. The solar abundance reference for [Fe/H] is from Grevesse & Sauval (1998): $A(X) = \log(N_X/N_H)+12$.
[a] Bolometric luminosities (Fanelli et al. 2022) have been estimated by using the dereddened 2MASS *K*-band magnitudes and bolometric corrections, as in Levesque et al. (2005). Reddening has been estimated by interpolating the Schlegel et al. (1998) extinction maps and applying the corrections by Schlafly & Finkbeiner (2011).

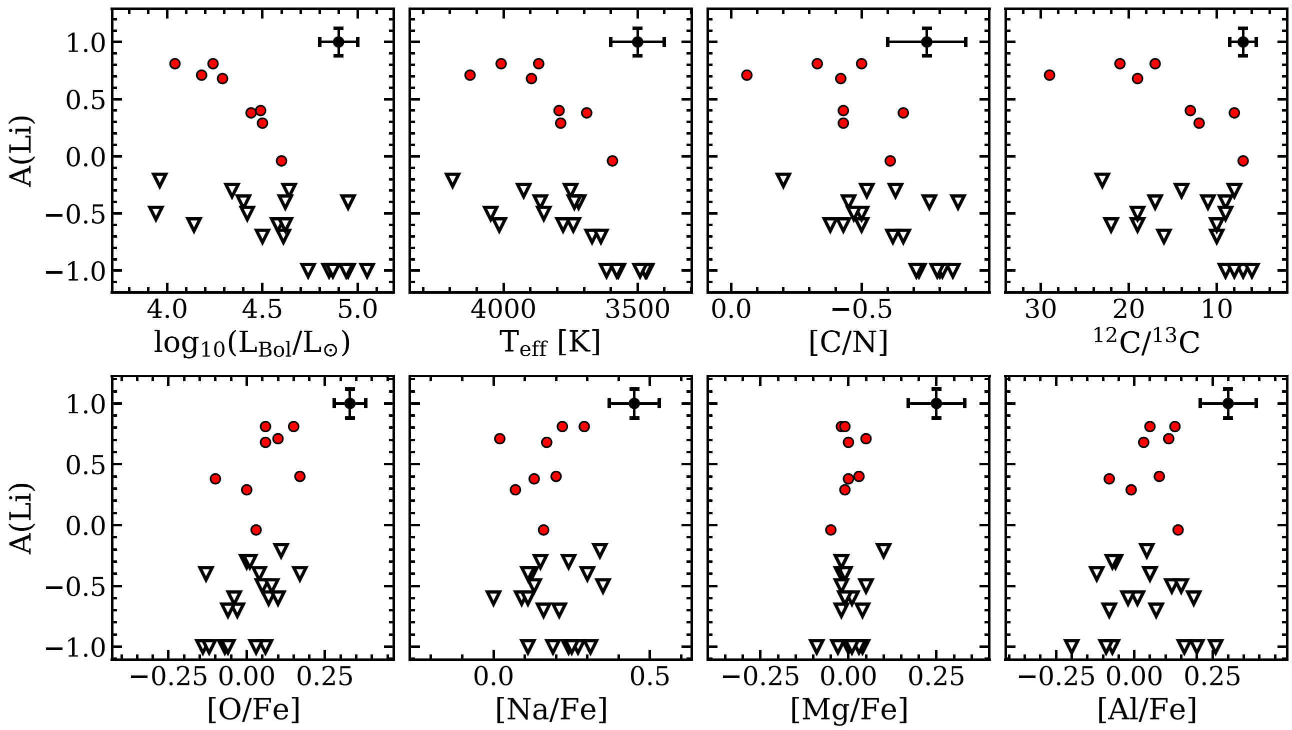

Figure 2. Lithium abundances (dots) or upper limits (triangles) as a function of the stellar bolometric luminosity, effective temperature, [C/N], $^{12}C/^{13}C$, [O/Fe], [Na/Fe], [Mg/Fe], and [Al/Fe] from Fanelli et al. (2022) for the observed 27 RSGs in the Perseus complex.

the mixing processes in the stellar interiors, suggesting that Li is more abundant in less mixed stars, where superficial Li is detectable. At variance, there is no evidence of any trend between the Li abundance and the [Mg/Fe], [Al/Fe], [O/Fe], or [Na/Fe] abundance ratios, nor of any difference in the distributions of these abundance ratios among RSGs with and without Li detection.

3. Discussion and Conclusions

The modeling of the RSG stellar structure and nucleosynthesis is complex, depending on a number of recipes and free parameters for the treatment of convection, mass loss, etc. (see, e.g., Fanelli et al. 2022, and references therein), which are still far from being properly constrained by observations.

Normally, Li is generally expected to be largely depleted in the atmospheres of evolved, massive stars, hence also in these RSGs, due to convective dilution with the internal layers, where Li is quickly burned. However, lithium has occasionally been detected in massive asymptotic giant branch (AGB) and super-AGB stars. These stars are expected to experience hot-bottom burning (HBB; Sackmann & Boothroyd 1992), i.e., proton-capture nucleosynthesis at the base of the outer envelope. The HBB process is activated when the temperature at the bottom of the envelope reaches 40 MK, and it can alter the abundances of CNO, Na, Al, Mg, and the $^{12}C/^{13}C$ isotopic ratio. At this temperature the Cameron–Fowler mechanism (Cameron & Fowler 1971) can also act, and Be^7 is transformed into Li^7 by electron capture and transported to cooler layers in the outer atmosphere, where it can temporarily survive (see, e.g., Siess 2010; Ventura & D'Antona 2010, 2011; Ventura et al. 2011; Lyubimkov et al. 2012; Ventura et al. 2013, and references therein). In these stars, the lithium yield is dramatically dependent on the adopted mass-loss formulation. Whether HBB and the Cameron–Fowler mechanisms could also work efficiently in RSGs with more massive progenitors is something that should be worth investigating in more detail.

The RSGs with Li detection have similar homogeneous half-solar metallicity, 10–30 Myr ages, and spatial distributions to the other RSGs in the observed sample without Li. They also span a similarly wide range of luminosities ($\log_{10}(L/L_\odot) = 4$–4.6) and temperatures ($T_{\rm eff} = 3600$–4100 K), i.e., likely the same 9–14 $M_\odot$ mass range. The fact that we detect Li only in ≈30% of them may indicate that some stochastic effect could regulate the presence and affect the detection of Li in their atmospheres. Moreover, among the RSGs with detected Li, there is evidence that the progenitor mass and the degree of mixing should matter in determining the amount of Li on the stellar surface, with higher abundances being found in somewhat less massive and/or less mixed RSGs. Given the chemical homogeneity of our sample of RSGs, there is no reason to assume an initial nonhomogeneous lithium abundance in the progenitors, hence mixing should definitely play a role in depleting Li on the stellar surface. Finally, the fact that RSGs with and without detected Li show similar [Mg/Fe], [Al/Fe], [O/Fe], and [Na/Fe] distributions, with low spread, suggests that the nucleosynthesis of Mg, Al, O, and Na in the RSG evolutionary stage should not be significantly altered.

Together with the mixing induced by convection in the post-MS stages, rotational mixing may also play a role in depleting Li in stellar atmospheres. Frischknecht et al. (2010) tested their rotational mixing prescriptions by using the Geneva stellar evolution code to follow the evolutions of surface abundances of light elements (Li, Be, and B) in massive stars, using 9, 12, and 15 $M_\odot$ models with rotation, from the zero-age MS up to the RSG phase. They found that massive dwarfs (as RSG progenitors) that are fast rotators are already depleted in Li at the end of the MS evolution, while in slow rotators (i.e., with

$v_{MS}/v_{crit} \leqslant 0.1$, corresponding to vsin($i$) $\leqslant$ 50 km s^{-1}), it is somehow delayed, occurring in the the post-MS evolution.

Strom et al. (2005) provided rotational velocities in a sample of B0–B9 stars in h, χ Persei, with masses in the 4–15 $M_{\odot}$ range, thus including both MS and evolved blue/yellow supergiants. They used spectra at $R \approx 22{,}000$ and derived rotational velocities, with an average ≈10% uncertainty, from the line broadening of optical He I and Mg II lines. By inspecting their Table 1, one can see that in the 9–14 $M_{\odot}$ range only a relatively small fraction (23%) of the stars are slow rotators, with vsin(i) $\leqslant$ 50 km s^{-1}, while the majority of them, either MS or more evolved giants and supergiants, have vsin(i) in the 50–200 km s^{-1} range. Rotational velocities exceeding 200 km s^{-1} have mostly been measured in dwarfs with masses below 9 $M_{\odot}$.

The relatively low fraction (∼30%) of RSGs with Li detection in our sample is consistent with the fraction of slow rotators (23%) in the sample of the Strom et al. (2005) blue stars in the same range of masses as our RSGs. Hence, we can speculate that the Li could have survived the total disruption in those RSGs with slow rotator progenitors and/or that the Li could have experienced a secondary production, due, e.g., to a Cameron–Fowler-like mechanism, as in less massive AGB and super-AGB stars.

The discovery of Li in the atmosphere of RSGs definitely poses a new challenge for theoreticians of stellar evolution and nucleosynthesis, and self-consistent modeling of the RSG nucleosynthesis is definitely needed to understand the complex evolution of these massive stars.

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ORCID iDs

C. Fanelli https://orcid.org/0000-0002-4639-1364
L. Origlia https://orcid.org/0000-0002-6040-5849
A. Mucciarelli https://orcid.org/0000-0001-9158-8580
E. Dalessandro https://orcid.org/0000-0003-4237-4601

References

Alvarez, R., & Plez, B. 1998, A&A, 330, 1109
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Balachandran, S. C., Mallik, S. V., & Lambert, D. L. 2011, MNRAS, 410, 2526
Cameron, A. G. W., & Fowler, W. A. 1971, ApJ, 164, 111
Charbonnel, C., & Primas, F. 2005, A&A, 442, 961
Cretignier, M., Francfort, J., Dumusque, X., Allart, R., & Pepe, F. 2020, A&A, 640, A42
Cyburt, R. H., Fields, B. D., & Olive, K. A. 2008, JCAP, 2008, 012
Dalessandro, E., Varri, A. L., Tiongco, M., et al. 2021, ApJ, 909, 90
Dunkley, J., Komatsu, E., Nolta, M. R., et al. 2009, ApJS, 180, 306
Fanelli, C., Origlia, L., Oliva, E., et al. 2022, A&A, 660, A7
Frischknecht, U., Hirschi, R., Meynet, G., et al. 2010, A&A, 522, A39
Gahm, G. F., & Hultqvist, L. 1976, A&A, 50, 153
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, A&A, 649, A1
Grevesse, N., & Sauval, A. J. 1998, SSRv, 85, 161
Grisoni, V., Matteucci, F., Romano, D., & Fu, X. 2019, MNRAS, 489, 3539
Gustafsson, B., Edvardsson, B., Eriksson, K., et al. 2008, A&A, 486, 951
Levesque, E. M., Massey, P., Olsen, K. A. G., et al. 2005, ApJ, 628, 973
Lind, K., Asplund, M., & Barklem, P. S. 2009, A&A, 503, 541
Lyubimkov, L. S., Lambert, D. L., Kaminsky, B. M., et al. 2012, MNRAS, 427, 11
Negueruela, I., Alonso-Santiago, J., Tabernero, H. M., et al. 2020, MmSAI, 91, 114
Origlia, L., Dalessandro, E., Sanna, N., et al. 2019, A&A, 629, A117
Plez, B. 2012, Turbospectrum: Code for spectral synthesis, Astrophysics Source Code Library, ascl:1205.004
Randich, S. 2010, in IAU Symp. 268, Light Elements in the Universe, ed. C. Charbonnel (Cambridge: Cambridge Univ. Press), 275
Sackmann, I. J., & Boothroyd, A. I. 1992, ApJL, 392, L71
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Siess, L. 2010, A&A, 512, A10
Spite, M., & Spite, F. 1982, Natur, 297, 483
Strom, S. E., Wolff, S. C., & Dror, D. H. A. 2005, AJ, 129, 809
Ventura, P., Carini, R., & D'Antona, F. 2011, MNRAS, 415, 3865
Ventura, P., & D'Antona, F. 2010, MNRAS, 402, L72
Ventura, P., & D'Antona, F. 2011, MNRAS, 410, 2760
Ventura, P., Di Criscienzo, M., Carini, R., & D'Antona, F. 2013, MNRAS, 431, 3642
Warren, P. R. 1973, MNRAS, 163, 337