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EFFECTIVE TEMPERATURE CALIBRATION OF GALACTIC BA-TYPE SUPERGIANTS

This study aims to establish a homogeneous effective temperature scale for a large sample of Galactic blue supergiants by combining medium-resolution spectroscopy with multi-band spectral energy distribution analysis. The sample includes about 140 stars in the B7-A0 spectral range. As the main spectroscopic diagnostic, the equivalent-width ratio of the temperature-sensitive He I λ4471 and Mg II λ4481 lines was used. An empirical calibration was constructed from standard supergiants with reliably determined atmospheric parameters, and the resulting polynomial relation was applied to derive effective temperatures for the full sample. To verify the spectroscopic estimates, spectral energy distributions were compiled from ultraviolet, optical, near-infrared, and mid-infrared photometry and compared with theoretical stellar atmosphere models. The obtained results show that the adopted line-ratio index provides an efficient observational temperature indicator across the studied range and allows all program stars to be placed on a single internally consistent temperature scale. The spectral energy distribution analysis supports the spectroscopic results and serves as an independent consistency check of the derived parameters. The scientific novelty of the work lies in the development and application of a uniform calibration framework suitable for a large observational sample without requiring full detailed atmospheric modeling for each object. The results enlarge the empirical basis for the study of blue supergiants and provide a practical reference for future Galactic and extragalactic stellar investigations.

Keywords: BA supergiants, Galactic supergiants, temperature calibration, equivalent width ratio, spectroscopic diagnostics, spectral energy distribution.

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Галактикалық BA аса алып жұлдыздардың тиімді температурасын калибрлеу

Бұл зерттеудің мақсаты орташа айырымдылықтағы спектроскопия мен көпжолақты спектрлік энергия таралуын талдауды біріктіру арқылы галактикалық көк аса алып жұлдыздардың үлкен таңдауы үшін біртекті тиімді температура шкаласын құру болып табылады. Таңдама B7-A0 спектрлік аралығындағы шамамен 140 жұлдызды қамтиды. Негізгі спектроскопиялық диагностикалық көрсеткіш ретінде температураға сезімтал He I λ4471 және Mg II λ4481 сызықтарының эквивалент ені қатынасы пайдаланылды. Атмосфералық параметрлері сенімді анықталған стандартты аса алып жұлдыздар негізінде эмпирикалық калибрлеу жасалып, алынған полиномдық тәуелділік бүкіл таңдама үшін тиімді температураларды анықтауға қолданылды. Спектроскопиялық бағалауларды тексеру мақсатында ультракүлгін, оптикалық, жақын инфрақызыл және орта инфрақызыл фотометрия деректері негізінде спектрлік энергия таралулары құрастырылып, жұлдыз атмосфераларының теориялық модельдерімен салыстырылды. Алынған нәтижелер қолданылған сызықтар қатынасының индексі зерттеліп отырған бүкіл диапазонда температураның тиімді бақылаулық индикаторы болып табылатынын және барлық бағдарламалық жұлдыздарды өзара үйлесімді бірыңғай температуралық шкалаға орналастыруға мүмкіндік беретінін көрсетеді. Спектрлік энергия таралуын талдау спектроскопиялық нәтижелерді растайды және алынған параметрлердің сәйкестігін тәуелсіз тексеру құралы ретінде қызмет етеді. Жұмыстың ғылыми жаңалығы әрбір нысан үшін атмосфераны толық егжей-тегжейлі модельдеуді қажет етпестен, үлкен бақылаулық таңдамаларға жарамды бірыңғай калибрлеу тәсілін әзірлеу және қолдану болып табылады. Алынған нәтижелер көк аса алып жұлдыздарды зерттеудің эмпирикалық негізін кеңейтеді және болашақтағы галактикалық әрі галактикадан тыс жұлдыздық зерттеулер үшін практикалық анықтамалық негіз ұсынады.

Түйін сөздер: BA аса алып жұлдыздары, галактикалық аса алып жұлдыздар, температураны калибрлеу, эквивалент ендер қатынасы, спектроскопиялық диагностика, спектрлік энергия таралуы.

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Калибровка эффективной температуры галактических BA сверхгигантов

Настоящее исследование направлено на построение однородной шкалы эффективных температур для большой выборки галактических голубых сверхгигантов на основе сочетания спектроскопии среднего разрешения и анализа спектрального распределения энергии в широком диапазоне длин волн. Выборка включает около 140 звёзд спектрального диапазона B7-A0. В качестве основного спектроскопического диагностического параметра использовалось отношение эквивалентных ширин температурно-чувствительных линий He I λ4471 и Mg II λ4481. На основе стандартных сверхгигантов с надёжно определёнными атмосферными параметрами была построена эмпирическая калибровка, а полученное полиномиальное соотношение применено для определения эффективных температур всей выборки. Для проверки спектроскопических оценок были построены спектральные распределения энергии с использованием ультрафиолетовой, оптической, ближней инфракрасной и средней инфракрасной фотометрии и сопоставлены с теоретическими моделями звёздных атмосфер. Полученные результаты показывают, что принятый индекс отношения линий является эффективным наблюдательным индикатором температуры во всём исследуемом диапазоне и позволяет поместить все программные звёзды на единую внутренне согласованную температурную шкалу. Анализ спектрального распределения энергии подтверждает спектроскопические результаты и служит независимой проверкой согласованности полученных параметров. Научная новизна работы заключается в разработке и применении единой калибровочной схемы, пригодной для большой наблюдательной выборки без необходимости выполнения полного детального моделирования атмосферы для каждого объекта. Полученные результаты расширяют эмпирическую основу для исследования голубых сверхгигантов и представляют собой практическую опору для будущих исследований галактических и внегалактических звёзд.

Ключевые слова: BA-сверхгиганты, галактические сверхгиганты, калибровка температуры, отношение эквивалентных ширин, спектроскопическая диагностика, спектральное распределение энергии.

Introduction

Blue supergiants of mid-B to mid-A spectral types are luminous, relatively massive stars that occupy a short-lived but astrophysically important stage of stellar evolution. With typical masses of about 7–15 M$\odot$, they radiate most of their energy in the optical domain and therefore belong to the visually brightest stellar objects in galaxies. Owing to their exceptionally high luminosities, blue supergiants can be detected in external galaxies at distances of several to several tens of Mpc, which makes them valuable tracers of recent star formation, stellar evolution in the upper Hertzsprung–Russell diagram, and the chemical properties of young stellar populations.

Systematic studies of Galactic A- and BA-type supergiants have demonstrated both the diagnostic richness and the complexity of these objects. The pioneering series by [1] presented an extensive ultraviolet and optical atlas of A-type supergiants and analyzed their atmospheric parameters and projected rotational velocities, establishing an important observational basis for later quantitative work. Subsequent high-precision spectroscopic analyses [2] showed that reliable atmospheric parameters of Galactic BA-type supergiants can be obtained through a combination of hydrogen lines, ionization equilibria of metals, and spectro-photometric constraints, leading to improved calibrations of spectral type, intrinsic colors, and bolometric corrections. More recently, Weßmayer et al. [3] extended such quantitative analyses to Galactic B-type supergiants and confirmed that a careful treatment of the atmospheric structure and line formation is essential for deriving accurate stellar parameters and chemical abundances. However, these detailed studies were based on relatively modest samples, typically of a few tens of stars, and therefore do not yet fully cover the observational diversity of the nearby Galactic blue-supergiant population.

A larger sample is needed not only to improve empirical calibrations between observable quantities and fundamental parameters, but also to test how robust these calibrations remain across different luminosity classes, rotation rates, reddening conditions, and circumstellar environments. Such a data set is particularly useful for identifying purely observational diagnostics that can later be applied to more distant stars in the Galaxy and beyond, where full high-resolution spectroscopic modeling is not always feasible.

Although several recent projects have focused on blue supergiants using high-resolution spectroscopy, a complementary medium-resolution approach remains highly relevant. Medium-resolution spectra allow one to observe substantially larger samples in a homogeneous way and to derive temperatures, gravities, and reddening-sensitive characteristics with reasonable efficiency. When combined with spectral energy distribution (SED) analysis based on broad-band photometry from the ultraviolet to the infrared, such spectroscopy provides an independent cross-check of parameters inferred from line-profile modeling. This is especially important for blue supergiants, for which interstellar extinction, possible infrared excess, and the sensitivity of the continuum shape to Teff can significantly affect the final parameter determination. In this sense, the joint use of spectroscopy and SED fitting is not merely auxiliary, but forms a self-consistent observational framework for establishing reliable stellar parameters and testing empirical calibrations. In related classes of hot stars, such as objects with the Be and B[e] phenomena, circumstellar emission and binarity are known to affect both line profiles and infrared excesses, further emphasizing the need for caution when interpreting continuum-based diagnostics [4,5].

In the present project, we analyzed multiple spectra for about 140 Galactic supergiants in the spectral range B7–A0 down to V∼10 mag. The main goal is to derive Teff using a combination of medium-resolution spectroscopy and multi-band photometric SED analysis. Such a study is expected to enlarge the empirical basis established in earlier detailed analyses and to provide a homogeneous reference sample for future work on Galactic and extragalactic blue supergiants.

Materials and methods

As a first step of the spectroscopic analysis, we investigated the temperature-sensitive absorption lines He I λ4471 and Mg II λ4481. This line pair is widely used in the analysis of early- and intermediate-type stars because the relative strength of these features changes systematically with effective temperature, reflecting variations in the excitation and ionization conditions in the stellar atmosphere [6]. In particular, the ratio between the helium and magnesium lines provides a convenient observational indicator for stars in the B-A spectral domain, where the He I line gradually weakens toward lower temperatures, while Mg II becomes more pronounced.

The analysis was based on more than 1000 spectra of Galactic supergiants obtained in 2014-2026 at the Three College Observatory (TCO, North Carolina, USA). For each star, the measured line parameters were averaged over multiple spectra. The observations were carried out with the 0.81 m telescope equipped with a fiber-fed échelle spectrograph manufactured by Shelyak Instruments and an ATIK-460EX detector. The spectra have a resolving power of R∼12 000 and cover the wavelength range from about 3800 to 7900 Å without gaps between the spectral orders. This instrumental setup is well suited for the present program, since it provides adequate spectral resolution and signal quality for stars down to about V∼10 mag. For the brightest objects, the signal-to-noise ratio in the continuum reaches ∼100-200 within a few seconds, whereas for the faintest targets it is typically about

~50 after exposures of 2-3 h. The highest signal-to-noise ratio, reaching up to ~300, is achieved in the 4500-5500 Å region, which includes the diagnostic He I and Mg II lines used in this work.

The equivalent widths of the He I and Mg II lines were measured in the IRAF environment using a manual procedure. Prior to the measurements, all spectra were continuum-normalized in IRAF in a consistent manner. The local continuum was defined interactively in the vicinity of each line, taking into account the actual shape of the observed spectrum and avoiding distorted or blended regions wherever possible. The equivalent widths were then determined by direct integration of the line profiles relative to the normalized continuum. For consistency, the same line identifications and a uniform integration approach were applied to all spectra in the sample.

The empirical calibration was constructed for the range Teff ≈ 8000-20 000 K, which covers the typical effective temperatures of BA-type supergiants in our sample.

To establish an empirical temperature calibration, a set of standard stars with reliably determined atmospheric parameters was adopted from the spectroscopic study of BA-type supergiants [7]. Their effective temperatures, together with the measured equivalent widths of the diagnostic lines, are listed in Table 1. For each calibration star, the equivalent widths of He I 4471 and Mg II 4481 were measured in a homogeneous manner, and the line-strength ratio

$$R = \frac{EW(He\,I\,\lambda\,4471)}{EW(Mg\,II\,\lambda\,4481)}$$

was calculated. This ratio is temperature-sensitive because the He I line strengthens toward higher temperatures, whereas Mg II becomes relatively stronger at lower temperatures. The obtained R values were then compared with the corresponding literature effective temperatures of the calibration stars. To describe this dependence, we approximated the relation R(Teff) by an ordinary least-squares fit with a second-order polynomial,

$$R = a + b\,T_{eff} + c\,T_{eff}^2. \quad (1)$$

For each program star, the measured ratio was converted into Teff by solving the polynomial relation for the observed value of R.

The polynomial coefficients and their formal uncertainties were derived from the covariance matrix of the fit, while the root-mean-square deviation of the residuals was used to quantify the scatter of the calibration. A quadratic function was found to provide an adequate representation of the observed dependence over the temperature range covered by the calibration stars and relevant to the program stars.

For each target spectrum, the equivalent widths of He I and Mg II were measured, their ratio was calculated, and the resulting value was used to estimate Teff from the calibration relation above. In this way, the He I/Mg II ratio served as a purely observational temperature diagnostic tied to a set of standard stars with well-established parameters. Such an approach is especially useful for constructing a homogeneous temperature scale for a large sample when full detailed atmospheric modeling is not the primary step of the analysis.

As an additional verification of the temperatures derived from spectroscopy, spectral energy distributions were constructed for the target supergiants using photometric data from the ultraviolet to the mid-infrared. The observational material was compiled from major all-sky catalogs and literature sources covering several wavelength domains. Ultraviolet absolute fluxes were taken from the TD-1 catalog at 1565, 1965, 2365, and 2740 Å [8]. Optical Johnson UBVRI photometry [9] was adopted from the compiled photoelectric catalog. Strömgren-Crawford uvby [10] measurements were collected from the updated mean catalog and the classical compilation. Near-infrared JHKs photometry was taken primarily from 2MASS [11]; for the brightest objects, where saturation could affect the 2MASS measurements, these data were supplemented by the Catalog of Infrared Observations. Mid-infrared photometry in the W1–W4 bands was taken from the AllWISE data release [12].

The assembled photometric points were then compared with theoretical spectral distributions from the Castelli–Kurucz model atmosphere grid [13]. For each star, the model parameters were selected so as to provide the best overall description of the observed SED. In the present work, this procedure was used not as a fully independent detailed atmospheric analysis, but rather as an additional consistency check of the temperatures inferred from the spectroscopic calibration. The SED fitting therefore served to verify whether the continuum energy distribution, from the ultraviolet to the infrared, was compatible with the temperature estimates obtained from the He I/Mg II line ratio.

Table 1. Effective temperatures Teff of the standard stars and equivalent widths of the He I and Mg II lines employed in deriving the empirical calibration relation.

N	Star	Sp.Type	EW(He I)	EW(Mg II)	Teff, [K]
1	HD7902	B6 Ib	0.63	0.40	14 100
2	HD36371	B4 Ib	0.69	0.37	14 600
3	HD184943	B8 Ia	0.38	0.58	11 900
4	BS7699	B6 Ib	0.58	0.36	14 000
5	BS8020	B8 Ia	0.45	0.47	12 700
6	BS618	A1 Ia	0.12	0.64	9 200
7	BS641	A2 Iab	0.09	0.61	8 500
8	HD13744	B9 Iab	0.13	0.60	9 500
9	HD14433	A1 Ia	0.11	0.64	9 150
10	HD14489	A1 Ia	0.15	0.64	9 350
11	HD20041	A0 Ia	0.20	0.60	10 000
12	HD21291	B9 Ia	0.28	0.57	10 800
13	HD39970	A0 Ib	0.22	0.58	10 300
14	HD46300	A0 Ib	0.12	0.43	10 000
15	HD186745	B8 Ia	0.47	0.52	12 500
16	BS7573	A2 Ia	0.11	0.65	9 300
17	HD197345	A2 Ia	0.11	0.68	8 700
18	HD202850	B9 Iab	0.29	0.60	10 800
19	BS8334	A2 Ia	0.11	0.64	8 800
20	BS8345	A2 Ib	0.10	0.57	9 250
21	HD210221	A3 Ib	0.11	0.60	8 400
22	HD212593	B9 Iab	0.28	0.50	11 200
23	HD223960	B9 Ia	0.26	0.61	10 700
24	HD195324	A2 Iab	0.10	0.52	9 200
25	HD34085	B8 Ia	0.43	0.50	12 100
26	HD87737	A0 Ib	0.14	0.52	9 600
27	HD165784	A2 Iab	0.13	0.73	9 000

Results and discussion

Thus, the empirical calibration equation linking the spectroscopic index to the effective temperature has the form (Fig. 1)

$$R = 2.713 - 6.386 \times 10^{-4} T_{eff} + 3.972 \times 10^{-8} T_{eff}^2. \quad (2)$$

The resulting root-mean-square scatter of the calibration is RMS(4471/4481)=0.033. The root-mean-square scatter of the calibration was computed from the residuals between the observed equivalent-width ratios and the values predicted by the quadratic fit, as

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(R_i - R_{i,fit})^2}, \quad (3)$$

where R_i is the observed EW(HeI/MgII) ratio for the i-th calibration star and $R_{i,fit}$ is the corresponding value given by the polynomial calibration.

Using the calibration relation given by Equation (2), effective temperatures were recalculated for about 140 supergiants selected from [22]. For each object, Teff was derived from the measured ratio of the equivalent widths of He I and Mg II using the empirical polynomial relation obtained from the calibration stars. The resulting temperatures are presented in Fig. 2. This procedure provided a homogeneous temperature scale for the entire sample within a single calibration framework.

The effective temperatures derived from the empirical He I λ4471/Mg II λ4481 calibration were compared with literature estimates for a subset of program stars. The results are presented in Table 2. In most cases, the temperatures obtained from the calibration equation are in satisfactory agreement with previously published values, confirming that the adopted line-ratio index provides a reliable temperature diagnostic over the studied spectral range. At the same time, some differences are present for individual objects, which may reflect differences in observational material, analysis techniques, or the intrinsic uncertainties of the spectroscopic calibration and literature determinations.

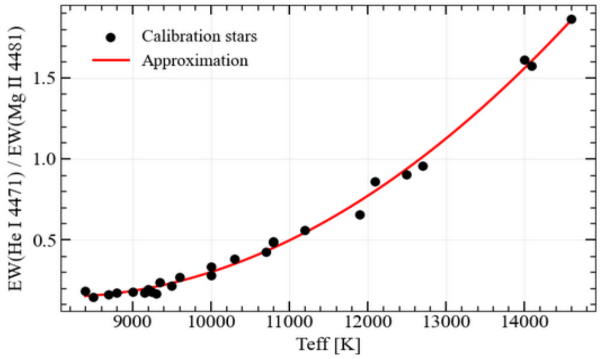

Figure 1 – Empirical relation between the equivalent-width ratio of He I λ4471 and Mg II λ4481 and effective temperature for the calibration supergiants. Black symbols show the standard stars, and the red curve gives the quadratic fit used for the temperature calibration.

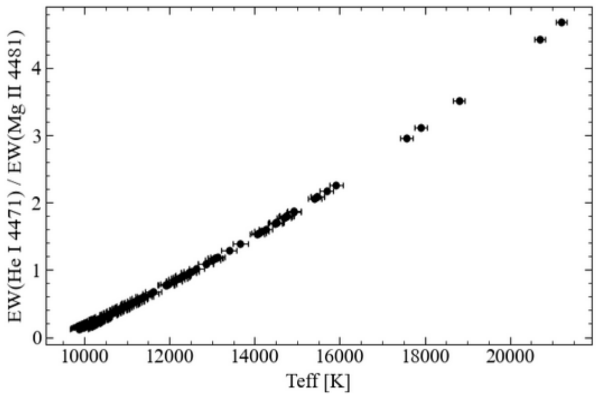

Figure 2 – Effective temperatures derived for the program stars from the empirical He I/Mg II calibration. The relation was applied uniformly to the full sample to place all objects on a homogeneous spectroscopic temperature scale.

Overall, the comparison shown in Table 2 supports the validity of the derived temperature scale and demonstrates that the proposed calibration can be used as a practical tool for homogeneous Teff estimates of Galactic blue supergiants.

Table 2. Effective temperatures of the program stars derived from the empirical He I λ4471/Mg II λ4481 calibration, compared with literature estimates.

N	Star	Sp.Type	Teff , [K]	Teff (lit) [K]	Ref
1	BD+60 2582	B7 Iab	12324 ± 184	11 900 ± 200	[2]
2	HD 5776	A2 Iab	10195 ± 207	10 715	[14]
3	HD 161695	A0 Ib	10268 ± 206	9 950	[15]
4	HD 175687	B9/A0 Ib	10153 ± 208	9 400	[16]
5	HD 16778	A1 Ia	9880 ± 211	9 550	[14]
6	HD 40589	A0 Iab	10841 ± 199	11 000	[17]
7	HD 46769	B7 Ib-II	15693 ± 156	13 920 ± 710	[18]
8	HD 67456	A3 Ib/II	9897 ± 211	9 500	[19]
9	HD 71833	B8 II	12847 ± 179	12 985	[20]
10	HD 35600	B9 Ib	11201 ± 195	11 000	[21]

The effective temperatures derived from the spectroscopic calibration were additionally checked against the observed spectral energy distributions. As illustrated in Fig. 3 for BS 25914, the model flux distribution calculated for temperatures in the vicinity of the spectroscopic estimate provides a satisfactory match to the observed photometric points over a wide wavelength range. In the literature, this object is identified with the B6 Ia/B5 Ia supergiant BD+56°884, for which the corresponding effective temperature on the Galactic B-supergiant scale is about Teff ≈ 13 500–14 000 K [23]. The agreement between the observed SED and the model distributions in this temperature interval supports the consistency of the spectroscopic calibration with the photometric data.

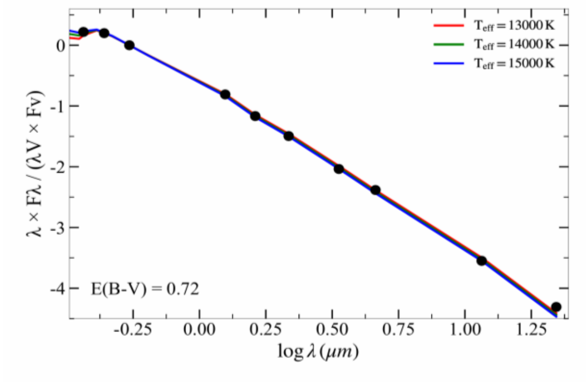

Figure 3 – Observed SED of BS 25914 compared with reddened model distributions computed for temperatures close to the spectroscopic estimate. The agreement supports the consistency of the adopted temperature calibration with the photometric data.

Conclusion

In this work, we constructed an empirical effective-temperature calibration for blue supergiants based on the equivalent-width ratio of the He I λ4471 and Mg II λ4481 lines. The calibration was derived from standard stars with well-established atmospheric parameters and approximated by a second-order polynomial relation.

The resulting calibration was then applied to a sample of about 140 Galactic supergiants, allowing their effective temperatures to be determined in a homogeneous way. This approach provides a consistent temperature scale for objects spanning the late-B to early-A spectral range and reduces the dependence on heterogeneous literature estimates.

An additional verification of the derived temperatures was carried out through comparison with spectral energy distributions. The agreement between the spectroscopic temperatures and the photometric SED fits confirms the overall reliability of the adopted calibration and supports its applicability to stars of similar spectral types.

Thus, the proposed method can be used as a practical tool for obtaining uniform temperature estimates for blue supergiants from spectroscopic data. At the same time, its accuracy depends on the quality of the observed spectra, the continuum normalization, and the applicability range of the calibration. Further improvement of the method may be achieved by extending the set of calibration stars and refining the relation using a broader spectroscopic sample.

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Author Contributions

Sh.T. Nurmakhametova: Conceptualization, Methodology, Investigation, Writing – Original Draft; **N.L. Vaidman**: Data Curation, Visualization, Writing – Review & Editing; **S.A. Khokhlov**: Supervision, Funding Acquisition, Project Administration; **A.T. Agishev**: Formal Analysis, Writing – Review & Editing.

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