SPECTRAL LUMINOSITY INDICATORS FOR FGK SUPERGIANTS AND CLASSICAL CEPHEIDS

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ABSTRACT. We have determined 28 relations between $\mathrm{M_v}$, T_{eff} and line depths ratios $\mathrm{R}_{\lambda 1}/\mathrm{R}_{\lambda 2}$. These relations have been used for the estimation of the absolute magnitudes $\mathrm{M_v}$ of 56 FGK supergiants with an error 0.05-0.30 mag (Table 1). The application range is F0–K0, luminosity classes I and II.

Key words: Stars: fundamental parameters; stars: absolute magnitudes; stars: supergiants.

1. Introduction

FGK-supergiants are very luminous stars and can be seen to large distances. However, being rare stars and residing in the galactic plane, they are are normally severely reddened. This fact presents a serious problem for studying supergiants, in particular when trying to infer their intrinsic luminosities. Cepheid Period–Luminosity (PL) relation remains the primary tool for determination of the distances within the Local Group and to the nearby galaxies. The absolute calibration of this relation relies on the accurate estimates of the distance of the calibrating Cepheids and their interstellar extinction and reddening. For non-periodic variable supergiants, obviously, PL relation is not applicable. Other techniques need to be developed for determination of the absolute stellar magnitudes and luminosities for a wide range of supergiants. In this work we turn to spectroscopy to search for the luminosity-sensitive features.

Calibrations of absolute magnitude from OI 7774 Å data are derived from narrow-band photometry and low dispersion spectroscopy for A0-G2 stars were presented by Arellano Ferro (1993). These calibrations allowed to estimate absolute magnitude with accuracies of 0.6 mag, they were improved (Arellano Ferro, Giridhar & Rojo Arellano, 2002) and then it was achieved accuracies of 0.38-1.5 mag for non-periodic supergiants and 0.42-0.43 mag for Cepheids. But the disadvantage of this method is the difficulty of observing and measuring the equivalent width of the OI 7774 Å feature in faint distant stars.

A further reaching approach is the calibration of the stellar absolute magnitude in terms of the photometric color indices. Arellano Ferro & Parrao (1990) were offered an independent calibration of the $uvby\beta$ photometric system to determine absolute magnitudes for luminous F-G supergiants, using as calibrators non-periodic yellow supergiants whose reddenings and absolute magnitudes are believed to be known. The similar and parallel research was presented by Gray (1991).

Andrievsky (1998ab) suggested to use the lines of the BaII to calibrate absolute magnitudes of non-periodic supergiants and low-amplitude Cepheids.

Apart from OI 7771-4 Å and Ba II, other lines in photospheric spectra of supergiants seem to evolve with luminosity. The ion lines behave similar to BaII, and the S I trough is strongest for supergiants with higher luminosity (if T_{eff} is constant). In particular, the ratio of the strengths of the Fe I and Fe II lines, was suggested as a potential luminosity indicator (for example, see Fig.1,2). The ratio Fe II/Fe I depends essentially on the strength of Fe II line, because Fe I line is about constant. In more luminous objects, Fe II is stronger because of a rapidly increasing Fe lI/Fe I ratio. Thus, the correlation between FeI/FeII ratio and luminosity is the effect of ionisation balance and NLTE effects.

Similar correlations are observed between luminosity and others ion line depths (for a given temperature). As example, Fig. 3 shows our measurements of depth of the Fe II 6129.69 Å and Si I 6155.14 Å lines. While the depths clearly increase with decreasing temperature, $\mathrm{R}_{\lambda 1}/\mathrm{R}_{\lambda 2}$ is approximately constant in all measurements. The resulting ratio 6129.69 FeII/6155.14 SiI vs Mv as shown in Fig. 4. The value increases towards higher luminosities.

The accuracy of spectroscopic luminosity determination could be improved if additional luminosity indicators were found that rely on species other than Fe. A number of such quantities has already been investigated (TiII/FeI, SI/FeI, FeII/NiI, ScII/FeI, YII/FeI etc). We selected in priority lines belonging to the iron-peak elements (such as Si, Ti, V, Cr, Fe, Ni) because they have a negligible star to star variation in element

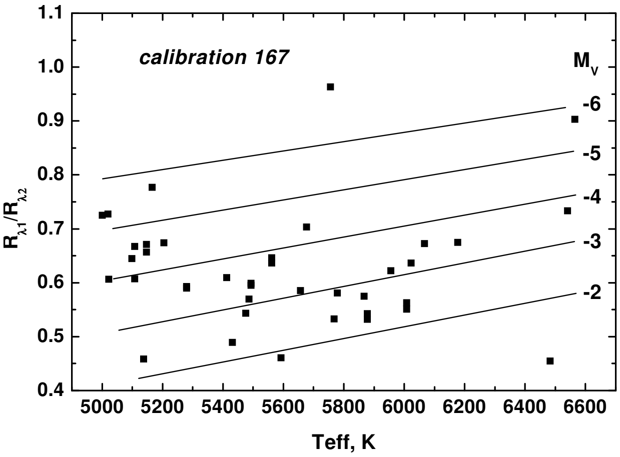

Figure 1: Calibration of the ratio 6129.69 FeII/6055.99 FeI in terms of the absolute magnitude M_v and temperature $T_{\rm eff}$ (calibration 167).

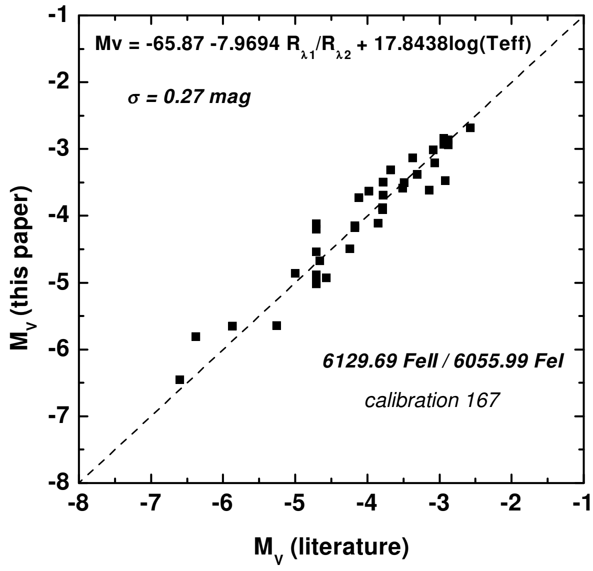

Figure 2: Comparison of our M_v with estimates from the literature for 6129.69 FeII/6055.99 FeI ratio (calibration 167).

abundances.

The aim of this paper is to determine M_v for F, G and K supergiant stars and Classical Cepheids from these new spectroscopic indicators.

2. Observations

The spectra of the FGK supergiants were obtained using the 1.93 m telescope of the Haute-Provence Observatoire (France) equipped with the echelle spectrograph ELODIE (Baranne et al. 1996) and retrieved from its online archive of spectra (Moultaka et al. 2004). The resolving power was R = 42 000 over the wavelength interval 4400-6800 ÅÅ, with a signal-to-noise ratio for each spectrum of S/N>100 (at 5500 ÅÅ). Initial processing of the spectra (image extraction, cosmic ray removal, flat-fielding, etc.) was carried out as described by Katz et al. (1998).

We also made use of spectra obtained with the Ultraviolet-Visual Echelle Spectrograph (UVES) instrument at the Very Large Telescope (VLT) Unit 2 Kueyen (Bagnulo et al. 2003). All supergiants were observed in two instrumental modes, Dichroic1 (DIC1) and Dichroic2 (DIC2), in order to provide almost complete coverage of the wave-length interval 3000-10 000 Å. The spectral resolution is about 80 000, and for most of the spectra the typical S/N ratio is 300-500 in the V band.

For Classical Cepheids we have used our published results (see Kovtyukh et al (2008) and references therein). We have used only phases of maximum radius (radial velocity V_{rad}=0 km s^{-1}) because at the phases of maximum radius (and close phases) an influence from the "dynamical" term on the luminosity indicators should be negligible. During the maximal compression of the Cepheid envelope the strong ther-

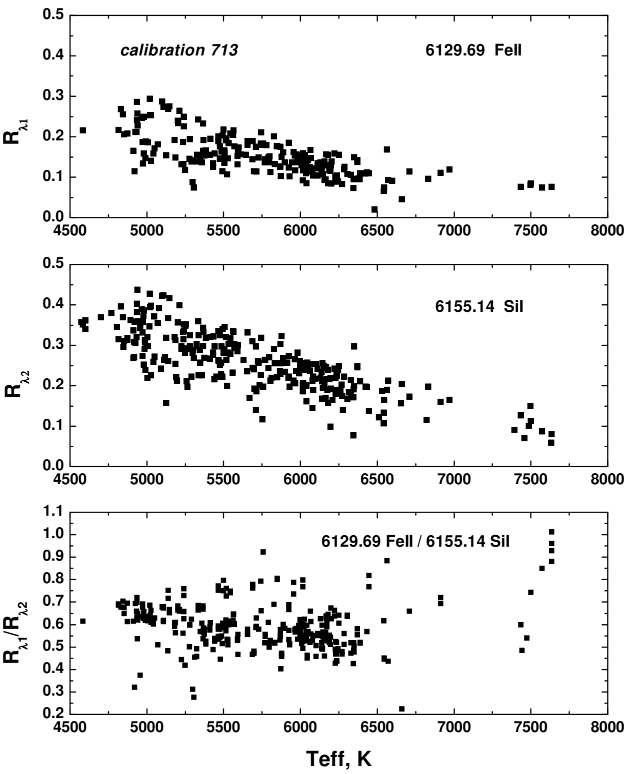

Figure 3: Behavior of depth of the FeII 6129.69 Å and SiI 6155.14 Å lines (calibration 713). See text for comments.

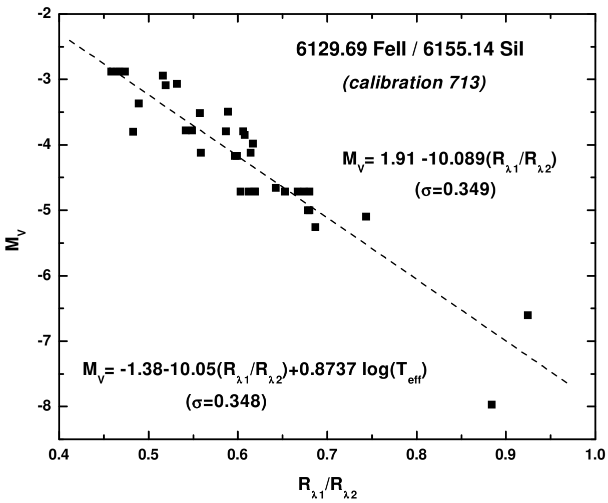

Figure 4: Comparison of our M_v with estimates from the literature for calibration 713 (see Fig.3).

mal and dynamical effects (like shock waves) are expected, while the phases at the maximum radius may be considered as the rather "quiet" ones enabling one to search for some dependencies between the Cepheids' M_v and their spectral luminosity indicators.

The further processing of spectra (continuum level location, measuring of line depths and equivalent widths) was carried out by us using the DECH20 software (Galazutdinov 1992). Line depths R_λ were measured by means of a Gaussian fitting.

3. Results

The next step was to choose the initial M_v for supergiants. This is a very important procedure since it affects the accuracy of the final luminosity scale, namely, the run of the systematic error with M_v and $T_{\rm eff}$. For 25 supergiants from our sample (see Table 1) we based the initial M_v estimates on the following 4 papers: Arellano Ferro & Parrao (1990), Gray (1991), Arellano Ferro (1993), Arellano Ferro, Giridhar & Rojo Arellano (2002). The effective temperature for supergiants has been determined using the calibrating relations from Kovtyukh (2007). These relations combine the effective temperature with a set of spectral line depth ratios. The internal accuracy of the effective temperature determined in this way is rather high in the temperature range 5000 K to 6500 K: typically 150 K or less (standard deviation or 10 to 20 K for the standard error). Another very important advantage of this method (or any spectroscopic method) is that it produces the reddening-free $T_{\rm eff}$ estimates. For 10 classical Cepheids we have used our previously published results (M_v and $T_{\rm eff}$).

Using the least-square method we have obtained 28 relations of the form:

$$M_v = a + b(logT_{\rm eff}) + c(R_{\lambda 1}/R_{\lambda 2}) + d(R_{\lambda 1}/R_{\lambda 2})^2,$$

where a,b,c,d – constants. Starting with an published value M_v, the relations are then self calibrated by an iterative process. Our final estimates have been compared to published M_v and show a good agreement (Fig. 5). In Table 1 we report M_v for 56 supergiants derived from our calibrations. Each entry includes the name of the star, $T_{\rm eff}$, mean M_v, error (σ), number of calibrations used, and the error of the mean (σ_{mean}).

The averaging of M_v obtained from 10-25 line ratios significantly reduces the uncertainty from a single calibration. The final precision we achieve is 0.05-0.30 mag (1 sigma), for the spectra of R=42 000, S/N=100–150. This can be further improved with higher resolution and larger S/N. We note that this error budget does not include the possible uncertainties that arise from the individual properties of stars, like rotation, chemical composition, binarity, etc.

4. Discussion

Having clarified the behaviour of observed FeI/FeII values, we now briefly discuss the use of line strengths ratios as luminosity indicators. We have shown that FeII/FeI correlates with luminosity. Thus, FeII/FeI should be the most direct and meaningful luminosity indicator. There are, however, uncertainties even in FeII/FeI as a spectroscopic luminosity indicator. First, the trend in the line is due to the combination of trends that are nonlinear in temperature, luminosity and also in [Fe/H] in the relevant ranges. In order to obtain luminosities from spectra, one has to choose an appropriate functional form (e.g. linear, second or third order) to fit the relation between line strength ratio, temperature and luminosity. Inaccuracies introduced by the use of such a functional form can easily be overlooked or misinterpreted as scatter. Second, intrinsic variations in the supergiants and their spectra limit the precision of spectroscopic luminosity indicators. Differences in the abundance distributions (e.g. He, C, N, O) among equally luminous supergiants are a possible reason for this.

One way to reduce the error would be to use a number of spectroscopic luminosity indicators, because different indicators respond differently to spectral peculiarities. Besides ratios like SiII/SiI, YII/FeI is also worth considering. Supergiants for which spectroscopic luminosity determination is unreliable could be identified if different indicators gave inconsistent luminosities.

Interesting trends have been found for SI 6046.00 Å and SI 6052.68 Å: SI/FeI and SI/SiI ratio correlates with luminosity like FeII/FeI. Sulphur has differ-

Table 1: The computed M_v for 56 supergiants.

HD	T_{eff} K	M_v mag	σ	N	σ (mean)	HD/BD	T_{eff} K	M_v mag	σ	N	σ (mean)
000611	5431	–2.69	0.38	18	0.09	109379	5117	–1.81	0.58	10	0.19
003421	5302	–1.75	0.47	17	0.12	125809	4837	–3.92	0.67	6	0.28
004362	5325	–3.26	0.43	19	0.10	136537	4960	–3.60	0.56	11	0.17
008890	6050	–3.06	0.16	18	0.04	159181	5220	–2.84	0.41	7	0.16
009973	6654	–7.13	0.30	10	0.09	174104	5657	–3.44	0.23	2	0.17
011544	5126	–3.54	0.33	4	0.17	179784	4956	–3.23	0.63	5	0.29
016901	5555	–2.91	0.18	21	0.04	182296	5072	–3.52	0.39	6	0.16
018391	5871	–6.47	0.37	12	0.11	183864	5323	–3.05	0.33	10	0.11
020123	5165	–2.28	0.37	9	0.13	185758	5390	–1.58	0.34	9	0.12
020902	6541	–4.96	0.08	3	0.05	187203	5710	–3.07	0.68	6	0.28
025056	5752	–3.31	0.54	6	0.22	187428	5911	–1.89	0.33	4	0.17
026630	5337	–3.12	0.30	9	0.10	188650	5669	–0.66	0.83	10	0.26
034248	6101	–4.41	0.47	13	0.13	190403	4894	–3.16	0.88	18	0.21
038808	5112	–2.43	0.42	10	0.13	191010	5269	–2.09	0.52	11	0.16
039949	5248	–2.76	0.38	20	0.09	192713	5028	–3.72	0.54	5	0.25
042454	5277	–3.67	0.24	17	0.06	194093	6202	–6.19	0.60	9	0.20
042456	4754	–4.44	0.42	13	0.12	195432	5872	–2.19	0.78	7	0.29
047731	4989	–3.77	0.39	4	0.20	202109	4976	–1.97	0.43	9	0.15
050372	4794	–4.02	0.74	15	0.19	204022	5375	–3.78	0.23	22	0.05
052220	5661	–2.90	0.29	20	0.07	204075	5287	–2.05	0.63	10	0.20
053003	5540	–2.89	0.31	11	0.09	204867	5466	–3.24	0.20	19	0.05
054605	6443	–7.83	0.24	7	0.09	205114	5224	–3.14	0.40	10	0.13
057146	5134	–3.47	0.21	21	0.05	209750	5210	–3.63	0.31	12	0.09
074395	5264	–2.94	0.24	21	0.05	214714	5424	–1.16	0.70	18	0.17
077912	4957	–3.05	0.85	12	0.25	216206	5003	–3.17	0.53	10	0.17
084441	5296	–1.62	0.15	5	0.07	219135	5479	–2.91	0.30	20	0.07
090452	6688	–7.24	0.65	10	0.21	249750	5475	–3.38	0.45	15	0.12
092125	5354	–2.15	0.27	12	0.08	+60 2532	6268	–4.30	0.74	3	0.43

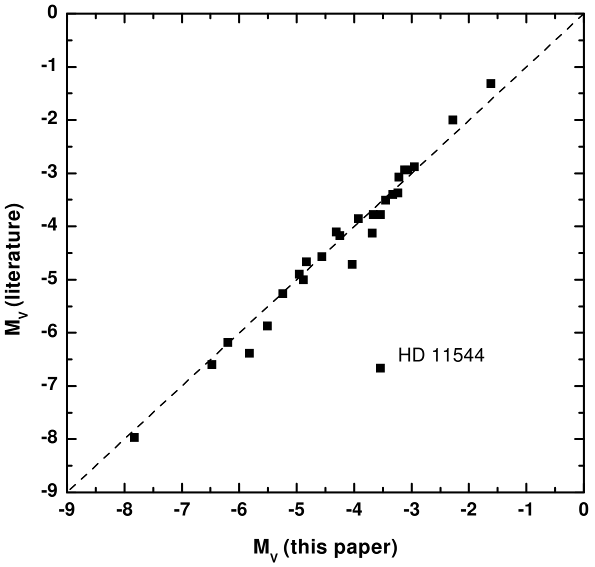

Figure 5: Comparison of our final M_v with estimates from the literature. The supergiant HD 11544 deviates from the least square fit found for FGK supergiants.

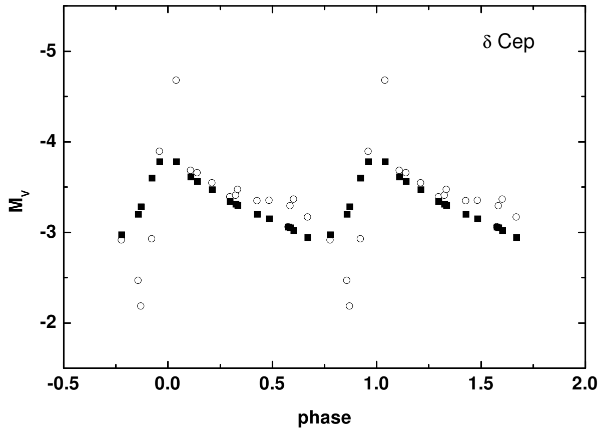

Figure 6: Comparison of our M_v with observed for Classical Cepheid δ Cep: filled squares – observations; open circles – calculations (showed are the individual phases for the Cepheid).

ent level structures and a higher ionisation potential than iron and silicon.

As noted by Andrievsky (1998ab), the Ba II 5853.6 Å and 6141.7 Å strengths could be used as a luminosity indicators for s-Cepheids. However, the relations between luminosity and BaII/FeI line ratios show large scatter.

However, the validity of these potential luminosity indicators still needs to be critically assessed in terms of the physical differences among supergiants with different abundances.

5. Conclusion

We showed that the ratio of the depths of FeII and FeI lines is larger for luminous supergiants (for a given temperature). Accordingly, FeII/FeI ratio could be used as a distance-independent spectroscopic luminosity indicator. Other spectral features (for example, FeII/NiI ratios) have subsequently been suggested as possible luminosity indicators. The BaII/FeI, YII/FeI ratios itself may be the best spectroscopic luminosity indicators for supergiants, but all these indicators show scatter which may be related to abundance distributions. As a result, we found that star HD 11544 can not be a member of a χ and h Per cluster.

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