THE PHYSICAL CHARACTERIZATION OF THE STARS

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Abstract:
The determination of the stellar parameters is of crucial importance for many fields of astrophysics, from the comprehension of the structure of the stars and their evolution, up to the determination of distances and the cosmological scale. This contribution reviews the main observational techniques and methods of calibration for the determination of the mass, radius, temperature, chemical composition and luminosity of stars.

Keywords: stars: chemical composition – stars: radius – stars: mass – stars: distance – stars: luminosity – stars: temperature

1 Introduction

The stars are the basic pieces of the universe and the understanding of their properties, structure, formation and evolution is one of the most important branches of astrophysics. To characterize the stars allows to characterize the galaxies and from them the universe as a whole. As it is well known, stars are formed in groups from the gravitational collapse of giant and cold clouds of molecular gas, take long episodes of production of energy through thermonuclear reactions in their interior with a length that depends on the mass, and die as highly compact objects. The life of an isolated star is mainly driven by their initial mass and chemical composition and along the years, it changes its observational properties, like size, luminosity, temperature, gravity and so on. Stars with the same initial properties have equivalent evolutions, and at the same evolutionary stage they have equal intrinsic luminosities. They may be seen with different apparent luminosities due to the attenuation by the distance and the extinction. This way, the comparison of observed luminosities of different stars (assumed to be instrinsically similar[1]) is a way to determine stellar distances, and actually it is the basis of the cosmic distance scale.

[1]The similarity of stars is derived from comparison of their spectral types, photometric colour indices, strenght of spectral lines, etc

Therefore, it is extremely important to characterize physically all of the stars, or in other words, it is important to determine the physical fundamental parameters (mass, radius, temperature, luminosity, composition).

Unlike other experimental sciences, astronomy and astrophysics cannot perform laboratory tests with stars. The astronomers must analyze the electromagnetic radiation coming from the star to deduce all the physical information. The most frequent observational methodologies, photometry and spectroscopy, allow to derive the flux measured by the observer in different wavelength ranges. The detailed analysis of this information allows to deduce the observable parameters of the stars: the temperature, gravity, luminosity and composition. The variation with time of the measured flux and of its wavelength distribution can be indicative of the presence of companion stars. In some of these cases, it is possible to determine the masses and the radii of the involved stars.

This contribution describes the principal methods that allow the determination of the physical stellar parameters, the current state of the knowledge and the future perspectives. We do not pretend to be complete, but to list the most used approaches.

2 Chemical composition

The chemical composition is measured from the intensities of the lines and bands of absorption. Here the most precise approach is to use high resolution spectroscopy. The fitting of synthetic spectral energy distributions (SED), computed with stellar atmosphere models, to the observed spectra provide the chemical abundances. To do that, effective temperatures, surface gravities and rotational velocities have to be assumed.

Among the catalogues of spectroscopic abundances, we mention the compilation by [9] that includes 5946 measurements of 3247 stars. A later edition by [10] contains [Fe/H] for FGK stars derived from high resolution and high S/N spectra. The catalogue by [14] contains detailed abundances of elements, including the α-elements, for 189 nearby field F and G dwarfs. Standard deviations of measurements are usually at the level 0.05–0.10 dex, and accuracies are at the level of 0.10–0.15 dex.

Spectroscopy needs long exposure times with large telescopes and in the case of faint stars or for large surveys, this can turn out to be highly prohibitive. The photometric measurements with intermediate bands located at suitable spectral ranges is an alternative and competitive approach, provided that the changes of the spectra due to changes of chemical composition have been calibrated through spectroscopic measurements 'a priori'. Several photometric systems have been designed for such a purpose, and among them we would like to mention the *uvby* Strömgren system [37], the Vilnius system [36] and the Gaia system [18].

Figure 1, extracted from [21], shows the comparison of spectroscopic and photo-

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metric determinations of [Fe/H]. The photometric derivation uses the *uvby* system and the calibration of [35]. In this case, the photometric calibration yields abundances slightly higher than the spectroscopic ones. Once corrected, the precisions are of the order of 0.15-0.20 dex.

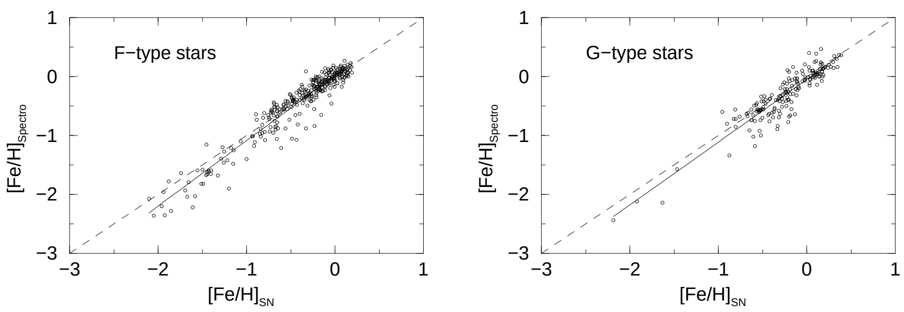

Figure 1: Comparison of the determination of chemical compositions from photometry and spectroscopy (extracted from [21]). The photometric system is the *uvby* system and the calibration is that of [35].

Guidelines for designing a photometric system sensitive to C,N,O and α-process elements were provided by [38] and [39]. The CaII H and K lines and MgI b triplet are the most sensitive direct indicators of [α/Fe] changes. Figure 2 (from [38]) shows the variation of the spectra when the effective temperature or the surface gravity or the chemical abundances change. The authors conclude that narrow bands placed on the Ca II H and K lines and Mg Ib triplet would allow to disentangle the changes due to variations of Fe- and α-elements. This idea was incorporated into the Gaia system [18] design.

3 Radius

Two techniques of observations are used to measure stellar angular diameters: the high angular resolution interferometry and the lunar occultations. While the first is a direct measure of the diameter, the second is a measure of the time needed for the star to be hidden rear the Moon, which is related with the angular diameter of the star and the motion of the Moon and the observer. The CHARM2 catalogue ([32]) is a compilation of direct measurements by high angular resolution methods, as well as indirect estimates of stellar diameters. A total of 8231 entries for 3238 unique sources are present.

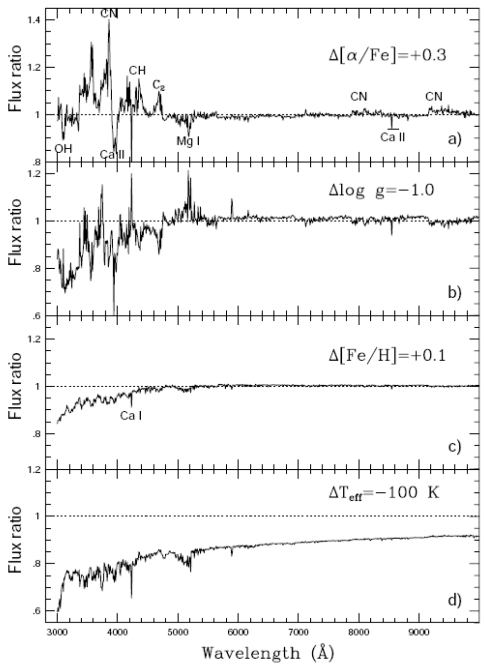

Figure 2: Relative variation of the flux energy with changes of effective temperature, surface gravity or chemical abundances (extracted from [38])

Other methods to derive angular diameters are based on the comparison of observed and theoretical spectral energy distribution. See [34] for a discussion, and [22] for an example. Figure 3 shows a comparison of semi-diameters derived by [22] with the above empirical determinations in the CHARM2 catalogue considering an uniform disk. The agreement is excellent. A crude comparison of both uniform disk and limb darkened values for about 1600 F, G and K stars indicates a ∼4% positive correction for limb darkening, of the same order of the dispersion shown in Figure 3.

Double-lined eclipsing binaries ([27]) and planetary transits ([8]) yield absolute stellar radii. Actually, radii relative to the semi-major axis of the orbit are derived from the light curves, and the inclination and the radial velocity curves complete the needed data to obtain the absolute radii. The light curves analysis takes into account corrections by limb darkening. The double-lined eclipsing binaries provide the most accurate determinations at present, which are ∼1–5%.

The Baade-Wesselink method applied to expanding or pulsating photospheres is

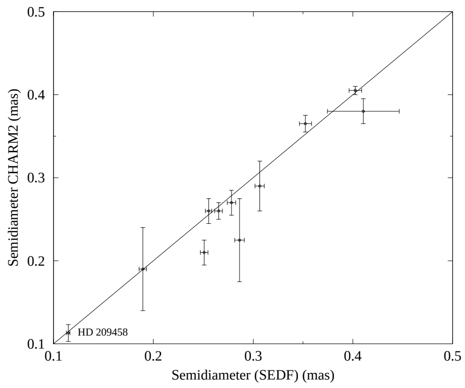

Figure 3: Comparison of angular semi-diameters computed from Spectral Energy Distribution Fit (SEDF) method [22] and from CHARM2 catalogue [32]. In the case of HD 209458, the comparison of the semi-diameter is between SEDF method an empirical determination from a high-precision transit light curve [8]. (Extracted from [22])

discussed by [34]. Under these special circumstances observed Doppler shifts of lines originating in moving photospheres may be used to derive absolute stellar diameters.

We would like to remark that the combination of temperatures and absolute radii allows to derive luminosities and, hence, direct distances with precisions almost equivalent to trigonometric parallaxes. This method has already allowed a precise determination (2-5%) of the distance of individual stars in LMC ([16] among others) and M31 [31]. The era of big telescopes will allow to extend substantially the sample and to reduce the current uncertainty.

4 Mass

The mass of a star can only be directly known through the analysis of its gravitational effect on the neighbouring objects, either stars or planets. In many cases, the multiple system is not resolved and it is discovered by periodic Doppler shifts of the spectral lines or periodic fluctuations of the apparent magnitude due to eclipses, because of the revolving motion of the star around the center of mass of the system.

In the case of double-lined spectroscopic binaries, the two stars have similar luminosity and the lines of both are distinguishable in the spectrum. This allows to derive the ratio of masses as well as the semi-major axis of the orbit by the factor sin$i$, being i the inclination of the orbit with respect the line of sight. If eclipses occur, the analysis of the light curve yields the inclination (among other parameters), and therefore the absolute individual masses can be derived.

The double-lined eclipsing binaries are extremely important, since they are the only case providing simultaneous determinations of individual masses and radii (see Sect. 3). The best reached precisions are of the order of 1-5% ([27], [4]). Such precisions are really needed for detailed tests of stellar structure and evolution models. Several tests have revealed discrepancies at both ends of the main sequence (high and low mass, see for instance [29] and [23]).

The masses of single stars can be estimated through Mass–Luminosity relationships based on binaries (see for instance [27, 4]), or through theoretical models. Theoretical stellar evolutionary models yield the temperature and luminosity (or radius) of a star of a given mass and chemical composition at a certain age. The location of a star in the observational colour–magnitude diagram can be transformed into a location in the theoretical luminosity–temperature diagram and from it estimate the mass and the age using the evolutionary tracks. Theoretical and observable quantities can be related with the use of appropriate calibrations and stellar atmosphere models. To cite one example, Asiain et al [5] derived stellar masses and ages for main sequence A-type stars with metallicity, effective temperature and surface gravity derived from $uvby - \beta$ photometry.

Microlensing phenomena can provide direct determinations of masses of single stars. When a star is acting as a lens, it is a non-massive lens that yields two unresolved images of the foreground object. The photocenter position of the composed image and its brightness change with the alignment, and the duration of the transient phenomena depends on the relative proper motions of the lens and the foreground object. The astrometric analysis of the photocenter displacement yields a direct measurement of the mass of the lens. The displacement is of a milli-arcsecond or less and hence an astrometric precision as small as few tens of micro-arseconds is needed. VERA (VLBI Exploration of Radio Astrometry) [17] and the next Gaia ESA's mission [25, 20, 26] are able to provide such precisions and so masses of single field stars.

5 Effective temperature

There are several approaches in the literature to compute effective temperatures. Except when applied to the Sun, very few of them are *direct* methods that permit an empirical measurement. Usually, *semi-empiric* or *indirect* methods are based to a certain extent on stellar atmosphere models. Among the *direct* approaches we find the remarkable work by [12], which is based on interferometric measurements of stellar angular semi-diameters θ and total fluxes $F_{\rm bol}$ at Earth ($F_{\rm bol} = \theta^2 \sigma T_{\rm eff}^4$). This work contains data for 32 stars of O5-F8 spectral types. Although being the most direct

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method for temperature determination, it still needs to rely at some extent on stellar atmosphere models to predict the energy in the wavelength range not covered by the observations and to correct the semi-diameters measurements for limb darkening.

The *indirect* methods are mainly based on the use of photometry, spectroscopy, or a combination of both. In photometry, the technique is to measure the radiation in the pseudo-continuum of the spectra, providing color indices free from chemical abundance signatures and so related with temperature (and interstellar absorption). As often as possible it is necessary to look for reddening-free indicators, like the intensity of certain spectral lines or bands (H_β line, TiO molecular bands, for instance), IR indices, etc. Or, either derive the interstellar absorption independently and correct the pseudo-continuum color indices. The synthetic photometry of SED predicted by atmosphere models, or the photometry of stars in [12] provide the necessary calibrations to relate photometric indices with temperatures. A good review of the problems involved in such temperature – color relations is provided by [6].

The use of IR photometry to determine effective temperatures was initially proposed by [7]. Their so-called Infrared Flux Method (IRFM) uses the ratio between the bolometric flux of the star and the monochromatic flux at a given infrared wavelength, both measured at Earth, as the observable quantity. This ratio is then compared with a theoretical estimate derived from stellar atmosphere models to carry out the determination of the effective temperature. The IRFM has been widely used by several authors, being most noteworthy the work by [1, 2, 3].

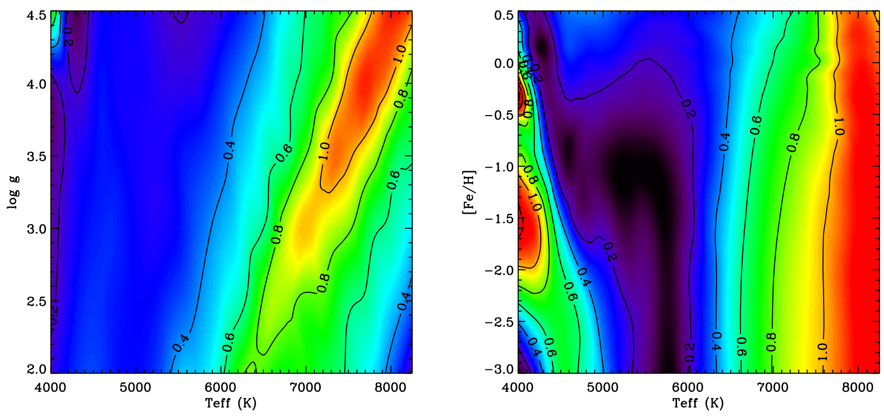

Figure 4: Relative error in temperature due to an uncertainty of 0.5 dex in gravity, derived using the Spectral Energy Distribution Fir method. Left: for solar metallicity. Right: for gravity 4.5. (extracted from [21])

The Spectral Energy Distribution Fit (SEDF) method proposed by [22] follows a somewhat different approach, namely the fit of the stellar spectral energy distribution from the optical (V) to the IR (JHK) using synthetic photometry computed from stellar atmosphere models. Unlike the implementation of the IRFM by [2], which averages temperatures derived individually for each IR band, the SEDF method takes into account the four bands simultaneously. In addition, and also unlike the IRFM, the bolometric flux is not required *a priori* but results self-consistently with the temperature determination. A fitting algorithm minimizes the difference between observed and synthetic photometry by tuning the values of the effective temperature and the angular semi-diameter. In addition, the BC can be obtained from these two parameters, and then, when the distance to the star is known, the luminosity is computed from the BC and the absolute magnitude in a given photometric band. The uncertainties of the derived parameters (temperatures, angular semi-diameter and BC) are estimated from the errors in the observed and synthetic photometry as well as in the assumed [Fe/H], $\log g$ and A_V. The relative error in temperature for several uncertainties of [Fe/H], $\log g$ and A_V are evaluated in [22]. As an example, Fig. 4 shows the relative error in temperature due to an uncertainty of 0.5 dex in gravity. For a sample of about 11 000 Hipparcos stars, and using 2MASS photometry ([13]), [22] derive temperatures with mean precisions of about 1%. Through an extensive comparison with determinations by other authors, [22] conclude that the effective temperature scale of FGK stars (4000–8000 K) is currently established with a net accuracy better than 0.5–1.0%.

Figure 5 shows the calibration by [22] of effective temperature as a function of the color index $V - K_S$ and the chemical composition.

In [28], direct temperatures for a sample of double-lined eclipsing binaries with accurate radii (1-2%) and relative error in the Hipparcos parallax below 20% are derived. The temperature is obtained from the Hipparcos parallax, the radius of the star, the visual magnitude and the bolometric correction, and thus, it is a rather direct method, since it only needs calibrations for the BC value. The comparison with photometric determinations of temperatures shows a small trend leading to the parallax based determination about 2-3% smaller than the photometric one. Due to the completely independent nature of the two temperature determinations, the authors conclude that a small systematic difference of about 0.012 dex is present in the temperature range covered by their sample (from 5000 K to 25000 K). Moreover, the two binary systems of the sample with the smallest relative errors in the Hipparcos parallax, β Aur and V1143 Cyg, agree with the photometric data. Highly accurate trigonometric parallaxes from the next Gaia ESA's mission [25, 20] will yield very accurate temperatures using this approach.

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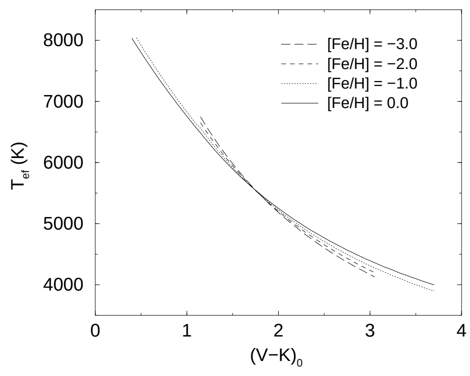

Figure 5: Relation between effective temperature and the color index $V - K_S$ for FGK dwarfs. The dependence with the chemical composition is shown as well. Figure extracted from [22]

6 Luminosity and distance

The absolute magnitude (and/or the luminosity) is, probably, the stellar parameter with the greatest cosmological transcendence. The direct measure of the intrinsic luminosity of the star is not possible. Only it can be realized if the effect of the interstellar absorption as well as the distance are known. The most precise measurement of the total energy released by the star is the combination of ground- and space-based observations with stellar atmosphere models to predict the energy in the wavelength range not covered by the observations.

Many absolute magnitude calibrations as a function of broad- or medium-band color indices or spectral types exists (see for instance [33]). All of them rely on primary calibrators with well known stellar distances. The accuracies of those calibrations range from 10 to 30% depending on the indicators used.

The large stellar distances make the measure of the trigonometric parallaxes only possible for the most nearby stars. The most accurate parallaxes nowadays available come from the Hipparcos mission [15]. Hipparcos constituted a great step forward in the measure of parallaxes, yielding ∼21 000 stars with relative errors lower than 10% and ∼50000 stars with relative errors lower than 20%. A complete review of the scientific exploitation of the Hipparcos data and specially the derivation of distances and luminosities can be found in [24]. The current knowledge of luminosities of the many types of stars across the HR diagram is discussed. The extremely precise parallaxes force the use of statistical methods to account for the biases in the observational samples. The next mission Gaia, to be launched at the end of 2011, will provide extremely precise parallaxes for some million stars including stars of all types.

7 Summary

We have listed several observational techniques and calibration methods to derive the fundamental properties of the stars. The most used are summarized as follows:

- High resolution spectroscopy yields the determination of chemical composition and allows the calibration of photometric indices sensitive to changes of the elements abundances

- High angular resolution interferometry and lunar occultations yield angular semi-diameters

- Comparison of observed and theoretical spectral energy distributions yield temperatures and semi-diameters. If distances are known, absolute radii can be derived

- Unreddened or reddening free color indices provide temperatures through suitable calibrations

- Photometric and spectroscopic observations of double-lined eclipsing binaries allow the simultaneous determination of individual masses and radii (at the level of 1-5% accuracy). Moreover, if the distance is known, the temperature can be derived. Instead, if the temperature is known, the distance can be computed

- Masses of individual stars can be estimated with a Mass-Luminosity relation or through stellar structure models

- Absolute magnitudes and luminosities can be determined 'directly' if parallaxes are known, or 'indirectly' through calibrations primarily based on a set of closer-by stars.

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References

[1] Alonso, A., Arribas, S., Martínez-Roger, C. 1995, A&A 297, 197
[2] Alonso, A., Arribas, S., Martínez-Roger, C. 1995, A&AS 117, 227
[3] Alonso, A., Arribas, S., Martínez-Roger, C. 1995, A&A 313, 873
[4] Andersen, J. 1991 A&ARv 3, 91
[5] Asiain, R., Torra, J., Figueras, F. 1997, A&A 322, 147
[6] Bell, R.A. 1997, in 'Fundamental Stellar Properties: The interaction between observations and theory' (Bedding et al. eds.), 159
[7] Blackwell, D. E. and Shallis, M. J. 1977, MNRAS 180, 177
[8] Brown, T. M., Charbonneau, D., Gilliland, R. L., Noyes, R. W., Burrows, A. 2001, ApJ 552, 699
[9] Cayrel de Strobel, G., Soubiran, C., Friel, E., Ralite, N., Francois, P. 1997, A&AS 124, 299
[10] Cayrel de Strobel, G., Soubiran, C., Ralite, N. 2001, A&A 159, 373
[11] Crawford, D.L. 1960, AJ 65, 487
[12] Code, A.D., David, J., Bless, R.C., Hanbury-Brown, R. 1976, ApJ 203, 417
[13] Cutri, R.M., Skrutskie, M.F., van Dyk, s., et al. 2003, http://www.ipac.caltech.edu/2mass/releases/allsky/doc/explsup.html
[14] Edvardsson, B., Andersen, J., Gustafsson, B., et al. 1993, A&A 275, 101
[15] ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
[16] Guinan, E. F., Fitzpatrick, E. L., Dewarf, L. E. et al 1998, ApJL 509, 21
[17] Honma, M. 2001, PASP 53, 233
[18] Jordi, C., Høeg, E., Brown, A.G.A. et al. 2006, MNRAS 367, 290
[19] Jordi, C., Luri, X., Masana, E., et al. 2002, Highlights of Astronomy, Vol. 12, 684
[20] Lindegren, L., Babusiaux, C., Bailer-Jones, C. et al. 2008, Procs. of the IAU Symp 248, A Giant Step: From Milli- to Micro-arcsecond Astrometry, W.J. Jin, I. Platais & M.A.C. Perryman, eds., in press
[21] Masana, E. 2004, Tesis doctoral, Universidad de Barcelona
[22] Masana, E., Jordi, C., Ribas, I. 2006, A&A 450, 735
[23] Morales, J.C., Ribas, I., Jordi, C. 2008 A&A in press arXiv:0711.3523
[24] Perryman, M.A.C. 2008, Astronomical Applications of Astrometry: A Review Based on Ten Years of Exploitation of the Hipparcos Satellite Data, Cambridge University Press (in press)
[25] Perryman, M.A.C., de Boer, K.S., Gilmore, G. et al. 2001, A&A 369, 339
[26] Perryman, M.A.C., de Boer, K.S., Gilmore, G. et al. 2000, GAIA, Composition, Formation and Evolution of the Galaxy, Concept and Technology Study Report, ESA-SCI(2000)4
[27] Popper, D.M. 1980 ARA&A 18, 115
[28] Ribas, I., Giménez, A., Torra, J., Jordi, C., Oblak, E. 1998, A&A 330, 600
[29] Ribas, I., Jordi, C., Giménez, A. 2000, MNRAS 318, 55
[30] Ribas, I., Jordi, C., Torra, J. 1999, MNRAS 309, 199

[31] Ribas, I., Jordi, C., Vilardell, F., et al. 2005, ApJL 635, 37
[32] Richichi, A., Percheron, I., Khristoforova, M. 2005, A&A 431, 773
[33] Schmidt-Kaler, T., 1982, in Landolt-Börnstein, eds. K. Schaifers and H.H. Voigt, Vol. II, Subvol. B, 453
[34] Scholz, M., 1997, in 'Fundamental Stellar Properties: The interaction between observations and theory' (Bedding et al. eds.), 51
[35] Schuster, W.J., Nissen, P.E. 1989, A&A 221, 65
[36] Straižys, V., Zdanavičius, K. 1965, Bull. Vilnius Obs. 14, 1
[37] Strömgren, B. 1966, ARA&A 4, 433
[38] Tautvaišienė G., Edvardsson B. 2002, Ap&SS, 280, 143
[39] Tautvaišienė G., Edvardsson B., Bartašiutė S. 2003, Baltic Astronomy 12, 532

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