

ON THE CALIBRATION OF THE STRÖMGREN PHOTOMETRIC SYSTEM FOR F AND G STARS

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RESUMEN

Se hace una revisión de las calibraciones del sistema de Strömgren *uvby- β* en términos de la temperatura efectiva, la magnitud absoluta, el cociente metales/hidrógeno y se estima la precisión de los parámetros derivados. Se hace notar la importancia de corregir los índices fotométricos por enrojecimiento interestelar y se discuten los efectos de la duplicidad. Con algunos ejemplos de las teorías de evolución galáctica y de la nucleosíntesis de la Gran Explosión, se demuestra la necesidad de valores muy precisos de los parámetros atmosféricos estelares.

ABSTRACT

Calibrations of the Strömgren *uvby- β* system in terms of effective temperature, absolute magnitude and metal-to-hydrogen ratio are reviewed and the accuracy of the derived parameters is estimated. The importance of correcting the photometric indices for interstellar reddening is stressed and duplicity effects are discussed. The need for very accurate values of the stellar atmospheric parameters is demonstrated with some examples from galactic evolution and Big Bang nucleosynthesis theories.

Key words: DUST, EXTINCTION — STARS: ABUNDANCES — STARS: FUNDAMENTAL PARAMETERS — GALAXY: EVOLUTION — EARLY UNIVERSE

1. INTRODUCTION

The structure of a star is —to a first approximation— given by a set of three basic parameters which may be specified as the effective temperature, T_{eff} , the absolute magnitude, M_V , and the metallicity, $[Fe/H]$. Knowledge of these parameters is of fundamental importance in several branches of astrophysics such as stellar structure and evolution and galactic structure and dynamics. Accurate values of the parameters are also needed when deriving abundances of the chemical elements from high resolution spectra and are therefore a necessary condition for observational studies of nucleosynthesis of the elements and chemical evolution in the Galaxy.

F and G main sequence stars and subgiants are of particular interest in this connection because they have ages ranging over the whole lifetime of the Galaxy. Furthermore, they have deep outer convection zones, which inhibit significant changes of the abundances of most elements in their atmosphere as a function of time. The observed composition of a star therefore represents the composition of the matter in the Galaxy at the time and at the place of the birth of the star. Hence, by studying the relations between chemical composition, ages and kinematics for F and G stars we may learn a lot about the chemical and dynamical history of the Galaxy.

The Strömgren *uvby- β* photometric system is particularly useful for F and G stars because it allows determination of all three basic parameters with high precision. In the present paper we review recent calibrations of this system and discuss the accuracy by which the basic parameters can be determined. The effects of interstellar extinction will also be considered. Finally, some examples of the importance of accurate values of the basic stellar parameters will be given.

2. INTERSTELLAR EXTINCTION

Calibrations of photometric systems in terms of T_{eff} , M_V and $[Fe/H]$ are valid only for reddening corrected indices. Most stars are reddened to some degree and it is therefore very important that one has a technique available to determine the color excess and to calculate intrinsic (reddening-free) indices. The Strömgren system has this facility, because both the H_β -line index, β , and the color index $b - y$ are sensitive functions of T_{eff} for F and early G stars. The β -index is independent of interstellar reddening, because the narrow and the broad filter used to measure β have the same effective wavelengths. Hence, the intrinsic color index $(b - y)_0$ can be determined from β . The first thorough calibration of $(b - y)_0$ vs. β was carried out by Crawford (1975). His calibration is valid for disk stars with metallicities $[Fe/H] > -0.5$. Later Olsen (1988) and Schuster & Nissen (1989a) have derived more elaborate calibrations valid also for metal-poor disk and halo stars. The rms of the residuals in these calibrations is about 0.009 mag, which is then the precision by which the color excess $E(b - y)$ can be determined. This corresponds to an error of 0.013 mag in $E(B - V)$.

The $(b - y)_0$ - β calibration is based on the assumption that there is no interstellar extinction within about 70 pc from the Sun. If this basic assumption is not true, systematic errors will occur in our determinations of T_{eff} , M_V and $[Fe/H]$ from the Strömgren indices. Hence, it is of considerable interest to compare the derived color excesses with an independent indicator of the presence of dust in the interstellar space. Since cold gas and dust probably occur together we may use interstellar absorption lines for such a test. Recently, Nissen & Schuster (1994) have obtained high-resolution spectra with the ESO 3.6-m telescope and its CASPEC echelle spectrograph for 50 halo stars. In some of the spectra interstellar Na I D1 and D2 lines are present and well separated from the stellar lines due to the large radial velocities of the halo stars. Table 1 lists the measured equivalent widths. The values for HD 140283 are taken from Gratton & Sneden (1988) and those of G166-45 from Hobbs & Thorburn (1991). The table also contains Na I column densities computed by the doublet ratio method (Strömgren 1948), color excesses from Schuster & Nissen (1989b) and distances from Nissen & Schuster (1991). As seen, all these stars with detected interstellar lines have a positive value of $E(b - y)$. In particular, it is interesting that the classical halo star, HD 140283, normally assumed to be unreddened, suffers from a small but significant degree of reddening.

Table 1. Equivalent Widths of Interstellar Na I Lines, Column Densities, Color Excesses and Distances for Halo Stars

Star	W(D1) mÅ	W(D2) mÅ	$\log N(\text{Na I})$ cm^{-2}	$E(b - y)$ mag	Distance pc
HD 24289	129	161	12.45	0.045	105
HD 25532	166	207	12.56	0.054	440
HD 140283	29	41	11.62	0.020	50
BD -17 267	31	57	11.50	0.029	180
CD -30 18140	38	52	11.77	0.025	160
G004-37	189	236	12.62	0.064	175
G084-29	44	96	11.62	0.019	135
G166-45	46	63	11.86	0.025	105
W1828	33	55	11.58	0.018	215

Sembach et al. (1993) have recently made a detailed study of interstellar Na I and Ca II toward distant B stars by observing the interstellar lines with high resolution. For a subset of these stars color excesses have been determined from Strömgren photometry. In Figure 1 the Na I column densities derived by Sembach et al. are plotted versus $E(b - y)$ together with the data from Table 1. As seen there is a rather good correlation between $N(\text{Na I})$ and $E(b - y)$,

$$N(\text{Na I}) = 1.14 \times 10^{14} E(b - y)^{1.37} \quad (1)$$

suggesting that gas and dust occur together and that the physical conditions in the nearby clouds, probed by the halo stars, and in the distant clouds, probed by B stars, are similar. More data is needed to see how tight the relation between $N(\text{Na I})$ and $E(b - y)$ is, but Figure 1 suggests that one can infer the color excess of a star from the measured strength of the interstellar D1 and D2 lines. This is of great importance for stars with spectral types later than G5, because for these stars the β -index is not a good indicator of T_{eff} and cannot be used to determine $E(b - y)$. Furthermore, it seems safe to assume that stars without interstellar Na lines are

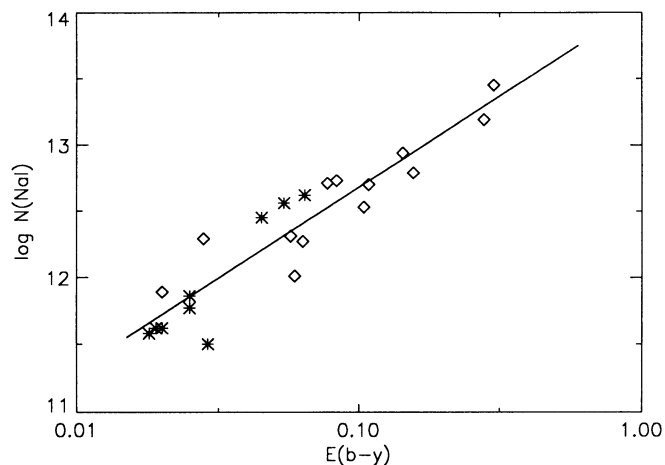


Fig. 1. Na I column densities versus color excesses derived from Strömgren photometry.
*, nearby halo stars from Nissen & Schuster (1994); ◊, distant B stars from Sembach et al. (1993).

not affected by interstellar extinction. The zero-point of the $(b-y)_0-\beta$ calibration may therefore be checked by the aid of such stars. In Figure 2 the $E(b-y)$ histogram of 23 stars from Nissen & Schuster (1994) with no detectable Na I lines is shown. The rms scatter of $E(b-y)$ is as small as expected (± 0.009) but the mean value is slightly positive, $\langle E(b-y) \rangle = 0.005$. This suggests that the zero-point in the $(b-y)_0-\beta$ calibration of Schuster & Nissen (1989a) (their Eq. (1)) should be increased with 0.005 mag.

A potential problem in deriving atmospheric parameters and interstellar reddening from photometric indices is that a substantial fraction of the stars may be unresolved binaries. However, as discussed by Schuster & Nissen (1989a) the duplicity effects on $E(b-y)$ derived from β are small, i.e., less than 0.01 mag, because binaries and single stars in the F and G spectral range follow nearly the same $(b-y)_0-\beta$ relation.

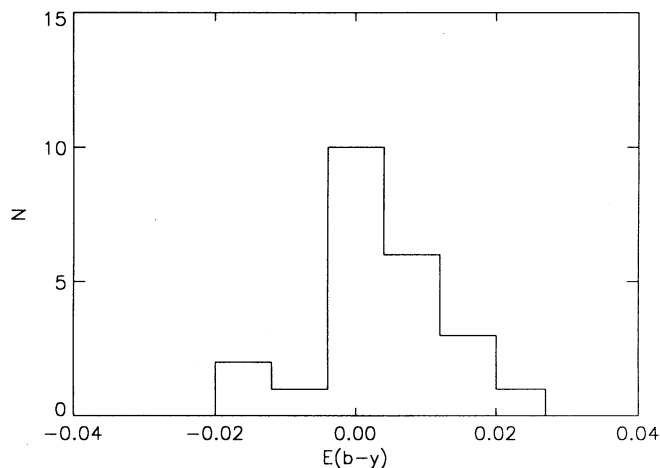


Fig. 2. The distribution of color excesses for stars without detectable interstellar Na I lines.

3. THE EFFECTIVE TEMPERATURE

The most direct method to determine the effective temperature of a star is based on the equation

$$\sigma T_{\text{eff}}^4 = f_{\text{bol}} (\theta/2)^{-2} \quad , \quad (2)$$

where f_{bol} is the observed bolometric flux and θ the angular diameter of the star. Among the F and G main sequence and subgiant stars only one, Procyon, has had its angular diameter measured by interferometric techniques (Hanbury Brown et al. 1974). As discussed by Code et al. (1976) the resulting effective temperature is $T_{eff} = 6510 \text{ K} \pm 130 \text{ K}$.

Blackwell & Shallis (1977) have introduced a more indirect way of determining T_{eff} , the so-called 'infrared flux method'. Eq. (2) is written as

$$\sigma T_{eff}^4 = f_{bol} \frac{F_\lambda}{f_\lambda}, \quad (3)$$

where F_λ and f_λ denote the monochromatic absolute and apparent flux, respectively. f_{bol} and f_λ are determined observationally, whereas F_λ is computed for a set of model atmospheres as a function of T_{eff} . By choosing in the infrared (J , K or L), F_λ is only weakly dependent on T_{eff} and Eq. (3) can be solved iteratively with respect to T_{eff} .

The infrared flux method has been applied for F and G stars by Saxner & Hammarbäck (1985), Magai (1987), and Arribas & Martínez Roger (1988, 1989). The authors claim an accuracy of T_{eff} ranging from about 100 K to 200 K. As shown by Saxner & Hammarbäck and Magai, $b-y$ is well correlated with T_{eff} for a given metallicity. Calibration equations valid for disk and halo stars, respectively, are given.

An alternative calibration of $b-y$ versus T_{eff} results from model atmosphere computations of the fluxes in the b and y bands. Recently Edvardsson et al. (1993) have constructed a new set of flux constant, LTE model atmospheres taking into account the line blanketing from millions of lines from the revised line lists of Kuruc (1989). The flux computed for the model of the solar atmosphere agrees well with the observed flux over the whole spectrum. Hence, the problem of the missing ultraviolet opacity, cf. Gustafsson & Bell (1979), has been solved. The $b-y$ index was computed for these model atmospheres by setting the zero point from the solar $b-y$ value as estimated from solar analogue stars (Cayrel de Strobel 1990) or 'solar twins' (Friel et al. 1993). The computations show that metallicity and surface gravity effects on $b-y$ are not negligible.

In Figure 3, T_{eff} determined from the theoretical calibration of $b-y$ is plotted versus the temperature determined by the infrared flux method. As seen the comparison is quite satisfactory for both disk and halo stars. For the disk stars the theoretical calibration leads to temperatures that are on the average 50 K higher than the empirical temperatures. In both cases the scatter is less than 100 K. Thus, it seems that effective temperatures can be determined to that accuracy. On the other hand, King (1993) has recently presented arguments for raising the temperature scale of halo stars with 150–200 K. His claim is supported by Fuhrman et al. (1993a, 1993b) who have derived T_{eff} from the profiles of hydrogen lines for a large set of stars. We conclude that the T_{eff} scale for halo stars should be further studied. For the time being systematic errors of 200 K cannot be excluded.

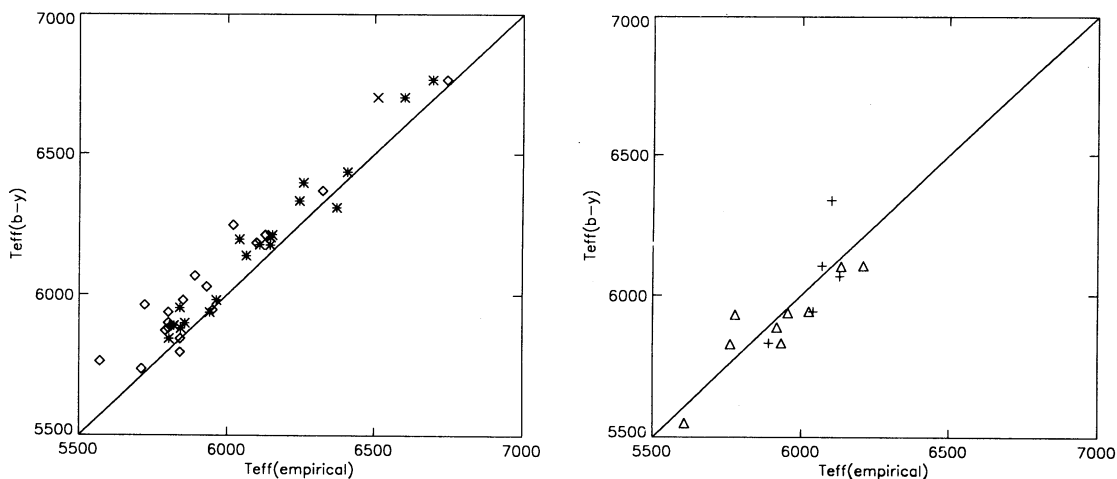


Fig. 3. Effective temperatures determined from the model atmosphere calibration of $b-y$ by Edvardsson et al. (1993) vs. T_{eff} determined by the infrared flux method. The left figure refers to disk stars with $-0.2 < [Fe/H] < 0.2$: *, Saxner & Hammarbäck (1985); ◊, Arribas & Martínez Roger (1988, 1989); x, Procyon with T_{eff} (empirical) determined by the angular diameter method. The right figure refers to halo stars with $-3.0 < [Fe/H] < -1.0$: Δ, Magai (1987), +, Arribas & Martínez Roger (1989).

A binary star may have a color index that deviates significantly from the color of the primary component. cluster & Nissen (1989a) have studied the effect for various combinations of main sequence, turn-off and subgiant stars. The maximum effect amounts to about 0.025 mag in $b - y$. The corresponding effect in T_{eff} is close to 200 K. Hence, information on duplicity is essential when one wants to determine accurate effective temperatures to be used for e.g., age determinations or abundance studies.

4. ABSOLUTE MAGNITUDE

The absolute magnitude of an F or G star may be determined from its position in the $c_1 - \beta$ or $c_0 - (b - y)_0$ diagram, i.e., the 'H-R diagram' of the Strömgren system. Calibrations valid for Pop. I F stars were first derived by Crawford (1975) and later improved by Nissen (1988). A more general calibration, particularly useful for F and G halo stars, has been derived by Nissen & Schuster (1991).

In Figure 4 we compare distances determined from the new General Catalogue of Trigonometric Parallaxes by van Altena et al. (1993) with distances derived from Strömgren photometry. Individual error bars are given for the parallax distances. The error of the photometric distance is about 15% or 0.06 dex. The sample of stars has been drawn from the high resolution spectroscopic study of 189 disk stars by Edvardsson et al. (1993), and only single stars or binary stars for which the secondary is more than 2.5 mag fainter than the primary have been plotted. As seen the overall agreement is rather satisfactory, but some stars deviate by more than σ . A possible explanation may be that the errors of the trigonometric parallaxes have been underestimated. We conclude that an improved calibration should await the publication of more accurate parallaxes from the *HIPPARCOS* satellite.

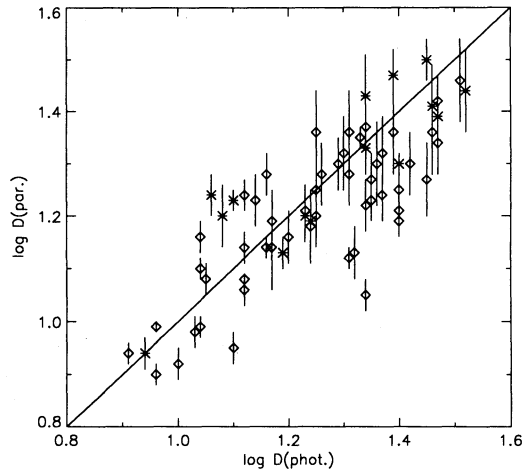


Fig. 4. Comparison of logarithmic distances (in pc) determined from Strömgren photometry and from parallaxes in the new catalogue by van Altena et al. (1993). Error bars indicate \pm the standard error. The error of the photometric distances is 0.06 dex. \circ refers to stars with $-0.4 < [\text{Fe}/\text{H}] < +0.3$ and $*$ to stars with $-1.0 < [\text{Fe}/\text{H}] < -0.4$.

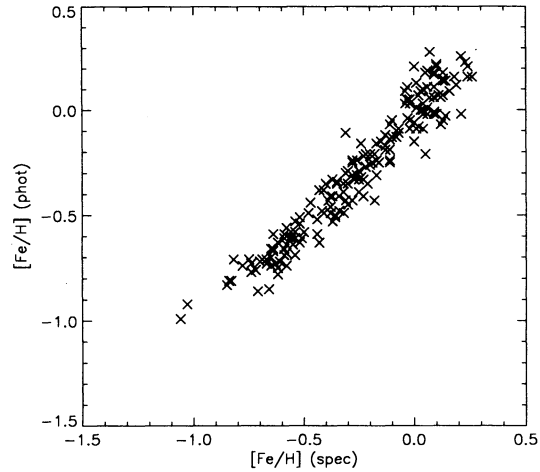


Fig. 5. $[\text{Fe}/\text{H}]$ -values determined from Strömgren photometry by the aid of the calibration of Schuster & Nissen (1989a) versus $[\text{Fe}/\text{H}]$ -values determined from high resolution spectroscopy by Edvardsson et al. (1993).

Whereas the M_V -calibration is reasonable accurate for disk stars, it is much more shaky for the metal-poor halo stars. As discussed by Schuster & Nissen (1989a) only 14 stars with $[\text{Fe}/\text{H}] < -1.0$ have parallaxes with errors less than 20 %, and of these only 4 belong to the important turnoff region of halo stars. Furthermore, errors of parallaxes quoted in literature are often unrealistic. The case of HD 140283, the famous metal-poor star with $[\text{Fe}/\text{H}] = -2.6$, illustrates this well. The latest published parallax is by Uggren et al. (1985), who quote $\pi = 0.0414 \pm 0.0127$ arcsec, corresponding to $M_V = 5.3 \pm 0.7$. According to this HD 140283 should be a dwarf star in contradiction with its position in the $c_0 - (b - y)_0$ diagram, where it occurs on the subgiant branch (Schuster & Nissen 1989b). Recently, however, a much more accurate parallax of HD 140283 has been measured at the US Naval Observatory, $\pi = 0.0124 \pm 0.0019$ arcsec, (Harrington 1993), corresponding to $M_V = 2.7 \pm 0.3$,

which confirms that HD 140283 is a subgiant. Similar accurate parallaxes for other halo stars would improve the M_V -calibration a lot.

If a binary star is assumed to be a single star, an error up to 0.75 mag in M_V may result. The corresponding maximum error in the distance will be about 40%. Similarly, if one is deriving the surface gravity from the position of a star in the $c_0-(b-y)_0$ diagram, errors up to 0.3 dex in $\log g$ may occur because of unrecognized duplicity.

5. THE METAL ABUNDANCE

The metal abundance of an F- or G-type star can be estimated from the Strömgren m_1 index. A calibration for F0-G2 disk stars with $[\text{Fe}/\text{H}] > -0.8$ was carried out by Nissen (1981) on the basis of $[\text{Fe}/\text{H}]$ values determined from photoelectric observations of selected groups of metal lines in narrow spectral bands. Later, Schuster & Nissen (1989a) derived a more general calibration that is valid for both disk and halo stars. This calibration is based on published $[\text{Fe}/\text{H}]$ -values determined from high resolution spectroscopy. Separate calibration equations are given for F and G stars.

Recently, Edvardsson et al. (1993) have published a survey of the chemical composition, ages and kinematics of 189 F and G disk stars. The stars were selected to have different metal abundances ranging from -1.0 to $+0.3$ in $[\text{Fe}/\text{H}]$. High resolution spectra were obtained and analyzed by model atmospheres. Altogether the abundances of 13 different elements were determined. The accuracy of $[\text{Fe}/\text{H}]$ is estimated to be 0.05 dex. Hence, these new data can be used for an important check of the calibration of the m_1 -index.

Edvardsson et al. (1993) compared their spectroscopic $[\text{Fe}/\text{H}]$ -values with photometric values determined from the Nissen (1981) calibration, which is based on m_1 and β . The agreement is good for the large majority of stars, but a group of 13 metal-rich stars deviate systematically in the sense that the photometric metallicities are 0.15 to 0.30 dex higher than the spectroscopic values. All of these stars, except one, have $b-y$ greater than 0.39. Thus, it seems that the m_1 - β calibration of Nissen (1981) breaks down for metal-rich, early G stars, probably because β is not a good indicator of T_{eff} for these stars. If instead, the Schuster & Nissen (1989a) calibration, based on m_1 and $b-y$, is used, then the agreement between the photometric and spectroscopic metallicities is excellent as shown in Figure 5. A linear regression fit to the data gives

$$[\text{Fe}/\text{H}]_{\text{phot}} = 1.012 [\text{Fe}/\text{H}]_{\text{spec}} - 0.034; \quad \sigma = 0.085 \quad (6)$$

It is clear that very accurate metal abundances can be derived from Strömgren photometry. It should, however, be noted that the Edvardsson et al. sample has been cleaned for binaries. As discussed by Schuster & Nissen (1989a) duplicity effects may cause errors in the derived $[\text{Fe}/\text{H}]$ up to 0.20 dex.

As we go to more and more metal deficient stars, m_1 is gradually losing sensitivity to $[\text{Fe}/\text{H}]$. Still at $[\text{Fe}/\text{H}] = -2.0$ it is possible to determine $[\text{Fe}/\text{H}]$ with a precision of about 0.2 dex. In order to test and improve the calibration of m_1 for metal-poor stars we need an extensive high resolution spectroscopic study of the chemical composition of halo stars like the Edvardsson et al. survey of disk stars.

6. GALACTIC EVOLUTION AND BIG BANG NUCLEOSYNTHESIS

Strömgren photometry may be used for large statistical studies of galactic structure and evolution. On the initiative of B. Strömgren an extensive Danish program was started some 15 years ago. The program and the first results are discussed in detail by Strömgren (1987). When finished, our knowledge about the age-metallicity-kinematics relations in the thick and the thin disk of the Galaxy will be much improved. Another example is the *uvby*- β photometry of 1264 high-velocity and metal-poor stars by Schuster et al. (1993), which has led to a better understanding of the formation and early evolution of the Galaxy.

Strömgren photometry is, however, also one of the best ways to determine accurate values of the basic parameters, T_{eff} and surface gravity g , in cases where we want to derive the detailed chemical composition of a star from a high resolution spectrum. Thus, accurate photometry and reliable calibrations are an important tool for the study of nucleosynthesis of the elements. The problem of the $[\text{O}/\text{Fe}]$ - $[\text{Fe}/\text{H}]$ relation in the galactic halo is a good example of this. Oxygen abundances can be derived from either the 7774 Å OI triplet (e.g. Tomkin et al. 1992) or OH lines in the near ultraviolet (Nissen et al. 1994). In both cases the results depend critically on the effective temperatures used. An error in T_{eff} of 200 K corresponds to an error in $[\text{O}/\text{Fe}]$ of 0.25 dex. Hence, the question of a possible trend and scatter in $[\text{O}/\text{Fe}]$ among halo stars can only be answered if temperatures can be determined with an accuracy of about 75 K.

Big Bang nucleosynthesis and the abundances of the light elements is another example of the importance of Strömgren photometry. The interest in this field has been remarkable during the last few years, mainly due to the detection of beryllium (Gilmore et al. 1992), boron (Duncan, Lambert, & Lemke 1992) and ${}^6\text{Li}$ (Smith, Lambert, & Nissen 1993) in metal-poor stars. As discussed by e.g., Walker et al. (1993) and Steigman et al. (1993) it is likely that these elements have been made by cosmic ray spallation of CNO elements and $+ \alpha$ reactions in the interstellar gas, i.e., there is no evidence for inhomogeneous Big Bang nucleosynthesis. Knowledge about the exact relation between the abundances of these elements and the abundance of iron or oxygen is, however, crucial for this interpretation. Again we need T_{eff} to an accuracy of 75 K and $\log g$ to an accuracy of 0.15 dex. Similar high accuracies are needed in order to detect a possible dispersion in the ${}^7\text{Li}$ abundance for extreme halo stars (Deliyannis et al. 1993) and to understand the nature of the newly discovered lithium-poor halo stars (Thorburn 1992; Spite et al. 1993).

7. CONCLUSIONS

We conclude that Strömgren *uvby- β* photometry of F and G stars is an important tool for the study of some of the most interesting problems in astrophysics. Accurate calibrations do exist for Pop. I F-type stars, but there is a need for improved calibrations for Pop. II stars. In particular we have noted that the T_{eff} scale for halo stars may be uncertain by up to 200 K, and that the absolute magnitude calibration hinges on uncertain parallaxes for a small sample of stars.

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DISCUSSION

Garrison: The biggest problem in determining solar twins is the observation of the color of the Sun. The star can only be observed at night and the Sun during the day. All methods are flawed in some way, so there is a large range of values, from $(B - V)_{\odot} = 0.62$ – 0.69 . Most recent carefully determined results indicate a value between 0.63–0.65.

Nissen: I agree that the uncertainty of the color of the Sun is an important error source in the model atmosphere calibration of $b - y$. The value used in the Edvardsson et al. (1993) calibration is $(b - y)_{\odot} = 0.406$, which corresponds to $(B - V)_{\odot} = 0.64$.

Wing: Concerning the calibration of the effective temperature, if one uses the infrared flux method, one needs the bolometric magnitude and this involves the flux calibration of the infrared photometry. For many years there has been a problem in that absolute flux measurements diverge from model-atmosphere flux distributions as one goes further into the infrared. Do you know any resolution of this problem?

Nissen: No, but I note that the infrared flux at wavelengths longer than 2.2μ is only about 5 % of the total flux for F and G stars. The largest uncertainty in T_{eff} determined by the infrared flux method is apparent due to the uncertainty in the absolute flux calibration of the J , K , and L magnitudes.

Peimbert: Is there a $[Fe/H]$ dispersion, larger than the observational errors, in stars of a given open cluster?

Nissen: The work of Edvardsson et al. (1993) did not include any clusters. There is no evidence from Strömgren photometry of 13 open clusters for a dispersion in $[Fe/H]$ in excess of the observational scatter (± 0.10 dex) with the possible exception of Praesepe (Nissen 1988). Cayrel et al. (1985, A&A, 146, 249) have found an anomalously low value of $[Fe/H]$ for two Hyades stars ($\Delta[Fe/H] = 0.10$ dex). However, these two stars probably have a high level of chromospheric activity, which affects the strengths of neutral iron lines.

Poveda: I found very exciting the relations you showed between beryllium and boron abundances on the one hand and iron on the other, which seem to confirm that the origin of the former is by spallation. This suggests that the deuterium and lithium we observe may not be of cosmological origin. Do you care to comment on the cosmological implications of the above relations?

Nissen: It's correct that cosmic ray processes have contributed to the lithium we observe in old halo stars. However, as shown by Walker et al. (1993) and Steigman et al. (1993), the contribution is small compared to the primordial production. Hence, the standard Big Bang model still agrees very well with the observed amount of lithium.

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