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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 ay be specified as the effective temperature, T_{eff}, the absolute magnitude, M_V, and the metallicity, [Fe/H]. nowledge of these parameters is of fundamental importance in several branches of astrophysics such as stellar ructure and evolution and galactic structure and dynamics. Accurate values of the parameters are also needed hen deriving abundances of the chemical elements from high resolution spectra and are therefore a necessary ndition 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 ;es ranging over the whole lifetime of the Galaxy. Furthermore, they have deep outer convection zones, which ·ohibit significant changes of the abundances of most elements in their atmosphere as a function of time. The)served composition of a star therefore represents the composition of the matter in the Galaxy at the time ıd at the place of the birth of the star. Hence, by studying the relations between chemical composition, ages ıd 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 particular useful for F and G stars because it allows ›termination of all three basic parameters with high precision. In the present paper we review recent ılibrations of this system and discuss the accuracy by which the basic parameters can be determined. The fects of interstellar extinction will also be considered. Finally, some examples of the importance of accurate ılues 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 correcte indices. Most stars are reddened to some degree and it is therefore very important that one has a techniqu available to determine the color excess and to calculate intrinsic (reddening-free) indices. The Strömgren syste has this facility, because both the H_β-line index, β, and the color index $b-y$ are sensitive functions of T_{eff} fo F and early G stars. The β-index is independent of interstellar reddening, because the narrow and the broa filter used to measure β have the same effective wavelengths. Hence, the intrinsic color index $(b-y)_0$ can b determined from β. The first thorough calibration of $(b-y)_0$ vs. β was carried out by Crawford (1975). H calibration is valid for disk stars with metallicities [Fe/H] > -0.5. Later Olsen (1988) and Schuster & Nisse (1989a) have derived more elaborate calibrations valid also for metal-poor disk and halo stars. The rms of th residuals in these calibrations is about 0.009 mag, which is then the precision by which the color excess E($b-$ 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 abou 70 pc from the Sun. If this basic assumption is not true, systematic errors will occur in our determinations T_{eff}, M_V and [Fe/H] from the Strömgren indices. Hence, it is of considerable interest to compare the derive color excesses with an independent indicator of the presence of dust in the interstellar space. Since cold g 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 eche spectrograph for 50 halo stars. In some of the spectra interstellar Na I D1 and D2 lines are present and we separated from the stellar lines due to the large radial velocities of the halo stars. Table 1 lists the measure equivalent widths. The values for HD 140283 are taken from Gratton & Sneden (1988) and those of G166- from Hobbs & Thorburn (1991). The table also contains Na I column densities computed by the doublet rat method (Strömgren 1948), color excesses from Schuster & Nissen (1989b) and distances from Nissen & Schust (1991). As seen, all these stars with detected interstellar lines have a positive value of E($b-y$). In particular, is interesting that the classical halo star, HD 140283, normally assumed to be unreddened, suffers from a sma 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) mA	W(D2) mA	log N(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 dista B stars by observing the interstellar lines with high resolution. For a subset of these stars color excesses ha been determined from Strömgren photometry. In Figure 1 the Na I column densities derived by Sembach al. are plotted versus E($b-y$) together with the data from Table 1. As seen there is a rather good correlati between N(Na I) and E($b-y$),

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

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

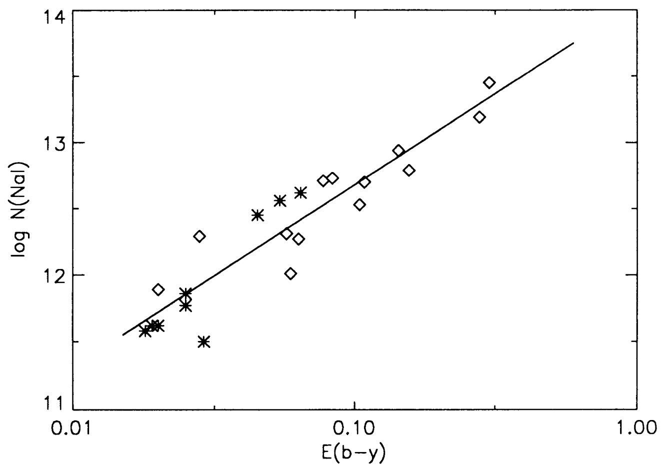


Fig. 1. Na I column densities versus color excesses derived from Strömgren photometry. $*$, nearby halo stars from Nissen & Schuster (1994); $\diamond$, distant B stars from Sembach et al. (1993).

ot affected by interstellar extinction. The zero-point of the $(b-y)_0$-β calibration may therefore be checked y the aid of such stars. In Figure 2 the E$(b-y)$ histogram of 23 stars from Nissen & Schuster (1994) with o detectable Na I lines is shown. The rms scatter of E$(b-y)$ is as small as expected (± 0.009) but the mean alue is slightly positive, $<$E$(b-y)>$ = 0.005. This suggests that the zero-point in the $(b-y)_0$-β calibration f 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 that a substantial fraction of the stars may be unresolved binaries. However, as discussed by Schuster & Nissen .989a) the duplicity effects on E$(b-y)$ derived from β are small, i.e., less than 0.01 mag, because binaries and ngle stars in the F and G spectral range follow nearly the same $(b-y)_0$-β relation.

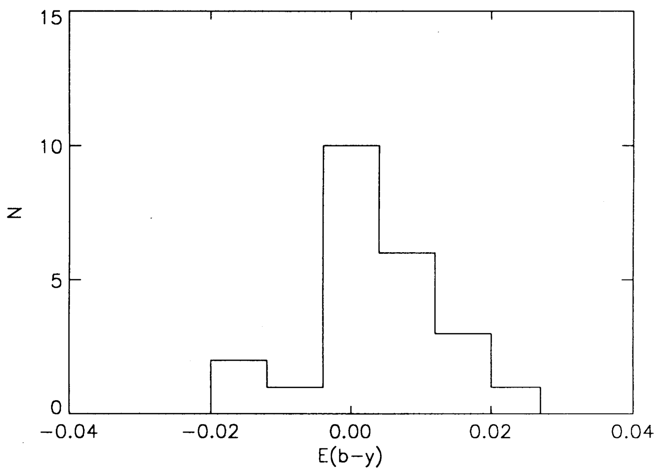


Fig. 2. The distribution of color excesses for stars without detectable interstellar Na I lines.

3. THE EFFECTIVE TEMPERATURE

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

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

where f_{bol} is the observed bolometric flux and θ the angular diameter of the star. Among the F and G mai sequence and subgiant stars only one, Procyon, has had its angular diameter measured by interferometri techniques (Hanbury Brown et al. 1974). As discussed by Code et al. (1976) the resulting effective temperatur is $T_{eff} = 6\,510$ K $\pm$ 130 K.

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

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

where F_λ and f_λ denote the monochromatic absolute and apparent flux, respectively. f_{bol} and f_λ are determine 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 wit 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 abou 100 K to 200 K. As shown by Saxner & Hammarbäck and Magain, $b-y$ is well correlated with T_{eff} for a give 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 i the b and y bands. Recently Edvardsson et al. (1993) have constructed a new set of flux constant, LTE mod 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 th whole spectrum. Hence, the problem of the missing ultraviolet opacity, cf. Gustafsson & Bell (1979), has bee solved. The $b-y$ index was computed for these model atmospheres by setting the zero point from the sola $b-y$ 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 temperatu determined by the infrared flux method. As seen the comparison is quite satisfactory for both disk and hal stars. For the disk stars the theoretical calibration leads to temperatures that are on the average 50 K high than the empirical temperatures. In both cases the scatter is less than 100 K. Thus, it seems that effecti temperatures can be determined to that accuracy. On the other hand, King (1993) has recently presente arguments for raising the temperature scale of halo stars with 150–200 K. His claim is supported by Fuhrma et al. (1993a, 1993b) who have derived T_{eff} from the profiles of hydrogen lines for a large set of stars. W conclude that the T_{eff} scale for halo stars should be further studied. For the time being systematic errors 200 K cannot be excluded.

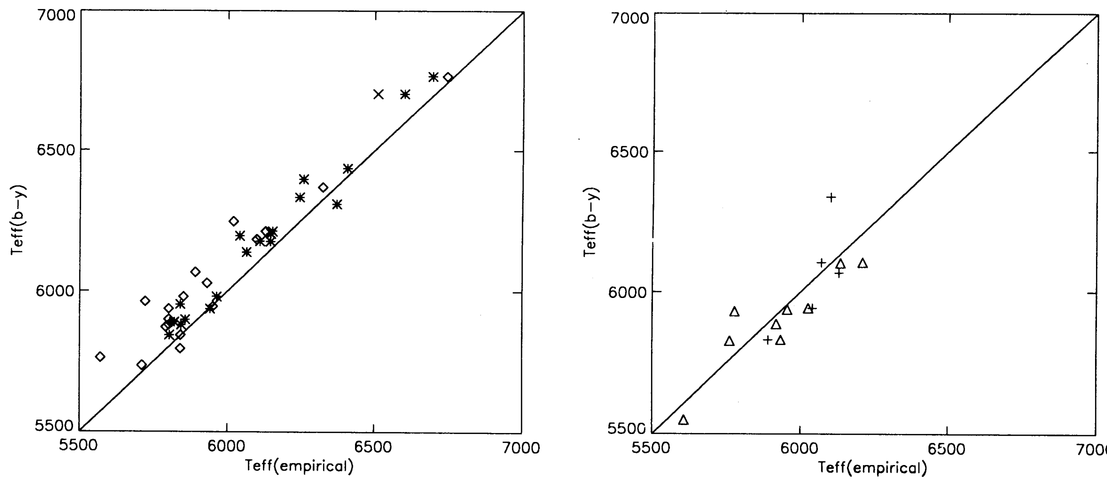


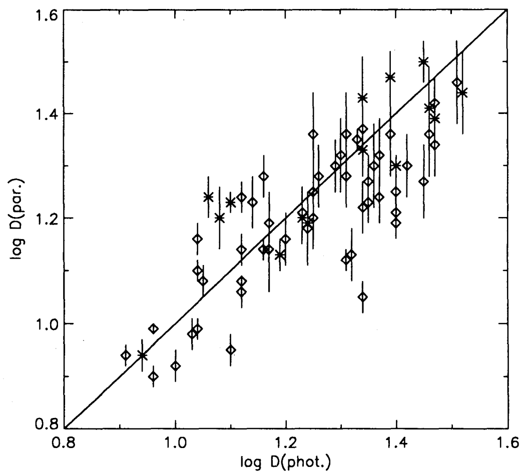
Fig. 3. Effective temperatures determined from the model atmosphere calibration of $b-y$ by Edvardsso et al. (1993) vs. T_{eff} determined by the infrared flux method. The left figure refers to disk stars with −0. < [Fe/H]< 0.2: $*$, Saxner & Hammarbäck (1985); $\diamond$, Arribas & Martinez Roger (1988, 1989); $\times$, Procyon wit T_{eff} (empirical) determined by the angular diameter method. The right figure refers to halo stars with −3.0 < [Fe/H]< −1.0: $\triangle$, Magain (1987), +, Arribas & Martínez Roger (1989).

A binary star may have a color index that deviates significantly from the color of the primary component. chuster & Nissen (1989a) have studied the effect for various combinations of main sequence, turn-off and ıbgiant stars. The maximum effect amounts to about 0.025 mag in $b - y$. The corresponding effect in T_{eff} ; close to 200 K. Hence, information on duplicity is essential when one wants to determine accurate effective ɜmperatures 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-β or c_0-$(b-y)_0$ iagram, i.e., the 'H-R diagram' of the Strömgren system. Calibrations valid for Pop. I F stars were first derived y Crawford (1975) and later improved by Nissen (1988). A more general calibration, particularly useful for F nd 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 y van Altena et al. (1993) with distances derived from Strömgren photometry. Individual error bars are given ɔr the parallax distances. The error of the photometric distance is about 15% or 0.06 dex. The sample of stars as been drawn from the high resolution spectroscopic study of 189 disk stars by Edvardsson et al. (1993), nd only single stars or binary stars for which the secondary is more than 2.5 mag fainter than the primary ave 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. Ve conclude that an improved calibration should await the publication of more accurate parallaxes from the *IIPPARCOS* satellite.



'ig. 4. Comparison of logarithmic distances (in pc) letermined from Strömgren photometry and from ɔarallaxes in the new catalogue by van Altena et al. 1993). Error bars indicate ± the standard error. Γhe error of the photometric distances is 0.06 dex. › refers to stars with $-0.4 <$ [Fe/H]$< +0.3$ and $*$ to ;tars with $-1.0 <$ [Fe/H]< -0.4.

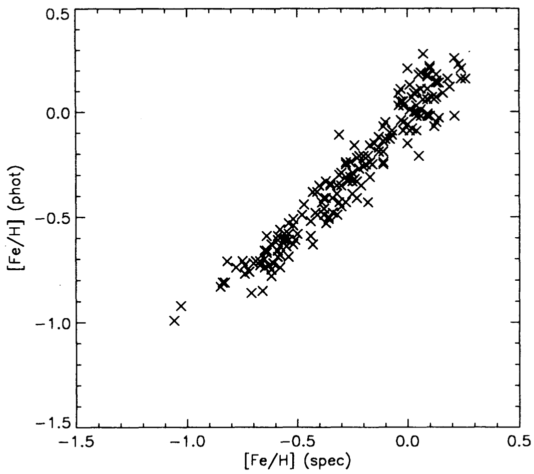


Fig. 5. [Fe/H]-values determined from Strömgren photometry by the aid of the calibration of Schuster & Nissen (1989a) versus [Fe/H]-values determined from high resolution spectroscopy by Edvardsson et al. (1993).

Whereas the M_V-calibration is reasonable accurate for disk stars, it is much more shaky for the metal-poor ıalo stars. As discussed by Schuster & Nissen (1989a) only 14 stars with [Fe/H] < -1.0 have parallaxes with ɜrrors less than 20 %, and of these only 4 belong to the important turnoff region of halo stars. Furthermore, ɜrrors of parallaxes quoted in literature are often unrealistic. The case of HD 140283, the famous metal-poor ;tar with [Fe/H] $= -2.6$, illustrates this well. The latest published parallax is by Upgren et al. (1985), who ʅuote $\pi = 0.0414 \pm 0.0127$ arcsec, corresponding to $M_V = 5.3 \pm 0.7$. According to this HD 140283 should be a lwarf 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 ıt 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 improv 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 correspondin maximum error in the distance will be about 40%. Similarly, if one is deriving the surface gravity from th 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 unrecognize 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 [Fe/H] > -0.8 was carried out by Nissen (1981) on the basis of [Me/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 [Fe/H]-values determined from high resolution spectroscopy. Separat calibration equations are given for F and G stars.

Recently, Edvardsson et al. (1993) have published a survey of the chemical composition, ages and kinematic of 189 F and G disk stars. The stars were selected to have different metal abundances ranging from -1.0 t $+0.3$ in [Fe/H]. High resolution spectra were obtained and analyzed by model atmospheres. Altogether th abundances of 13 different elements were determined. The accuracy of [Fe/H] is estimated to be 0.05 de 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 [Fe/H]-values with photometric values determine from the Nissen (1981) calibration, which is based on m_1 and β. The agreement is good for the large majorit of stars, but a group of 13 metal-rich stars deviate systematically in the sense that the photometric metalliciti are 0.15 to 0.30 dex higher than the spectroscopic values. All of these stars, except one, have $b-y$ great than 0.39. Thus, it seems that the m_1-β calibration of Nissen (1981) breaks down for metal-rich, early G star 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 spectroscop metallicities is excellent as shown in Figure 5. A linear regression fit to the data gives

$$[\mathrm{Fe/H}]_{phot} = 1.012\,[\mathrm{Fe/H}]_{spec} - 0.034; \qquad \sigma = 0.085 \;. \qquad (4$$

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

As we go to more and more metal deficient stars, m_1 is gradually loosing in sensitivity to [Fe/H]. Sti at [Fe/H] $= -2.0$ it is possible to determine [Fe/H] with a precision of about 0.2 dex. In order to test an improve the calibration of m_1 for metal-poor stars we need an extensive high resolution spectroscopic study 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 tl initiative of B. Strömgren an extensive Danish program was started some 15 years ago. The program and tl first result are discussed in detail by Strömgren (1987). When finished, our knowledge about the age-metallicit kinematics relations in the thick and the thin disk of the Galaxy will be much improved. Another example the *uvby*-β photometry of 1 264 high-velocity and metal-poor stars by Schuster et al. (1993), which has led 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 bas parameters, T_{eff} and surface gravity g, in cases where we want to derive the detailed chemical composition a star from a high resolution spectrum. Thus, accurate photometry and reliable calibrations are an importa tool for the study of nucleosynthesis of the elements. The problem of the [O/Fe]-[Fe/H] relation in the galact halo is a good example of this. Oxygen abundances can be derived from either the 7774 A O I triplet (e. Tomkin et al. 1992) or OH lines in the near ultraviolet (Nissen et al. 1994). In both cases the results deper critically on the effective temperatures used. An error in T_{eff} of 200 K corresponds to an error in [O/Fe] 0.25 dex. Hence, the question of a possible trend and scatter in [O/Fe] among halo stars can only be answer 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 ' Strömgren photometry. The interest in this field has been remarkable during the last few years, mainly ıe to the detection of beryllium (Gilmore et al. 1992), boron (Duncan, Lambert, & Lemke 1992) and ^{6}Li ;mith, Lambert, & Nissen 1993) in metal-poor stars. As discussed by e.g., Walker et al. (1993) and Steigman al. (1993) it is likely that these elements have been made by cosmic ray spallation of CNO elements and + α reactions in the interstellar gas, i.e., there is no evidence for inhomogeneous Big Bang nucleosynthesis. nowledge about the exact relation between the abundances of these elements and the abundance of iron or xygen is, however, crucial for this interpretation. Again we need T_{eff} to an accuracy of 75 K and log g to ı accuracy of 0.15 dex. Similar high accuracies are needed in order do detect a possible dispersion in the ^{7}Li ɔundance for extreme halo stars (Deliyannis et al. 1993) and to understand the nature of the newly discovered :hium-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 ɔme of the most interesting problems in astrophysics. Accurate calibrations do exist for Pop. I F-type stars, ıt there is a need for improved calibrations for Pop. II stars. In particular we have noted that the T_{eff} scale ' halo stars may be uncertain by up to 200 K, and that the absolute magnitude calibration hinges on uncertain ırallaxes 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 sta can only be observed at night and the Sun during the day. All methods are flawed in some way, so there is large range of values, from $(B-V)_\odot = 0.62$–0.69. Most recent carefully determined results indicate a val 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 atmosphe calibration of $b-y$. The value used in the Edvardsson et al. (1993) calibration is $(b-y)_\odot = 0.406$, whi corresponds to $(B-V)_\odot = 0.64$

Wing: Concerning the calibration of the effective temperature, if one uses the infrared flux method, one nee the bolometric magnitude and this involves the flux calibration of the infrared photometry. For many yea there has been a problem in that absolute flux measurements diverge from model-atmosphere flux distributio 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 % ot the tot 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 cluste

Nissen: The work of Edvardsson et al. (1993) did not include any clusters. There is no evidence from Strömgr photometry of 13 open clusters for a dispersion in [Fe/H] in excess of the observational scatter (± 0.10 de with the possible exception of Praesepe (Nissen 1988). Cayrel et al. (1985, A&A, 146, 249) have found anomalously low value of [Fe/H] for two Hyades stars (Δ[Fe/H] = 0.10 dex). However, these two stars probab 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 o hand and iron on the other, which seem to confirm that the origin of the former is by spallation. This sugges that the deuterium and lithium we observe may not be of cosmological origin. Do you care to comment on t cosmological implications of the above relations?

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

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