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Strömgren $uvby$ photometry of B-type stars from the Palomar–Green Survey

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Abstract. We present Strömgren *uvby* photometry for a sample of 31 high Galactic latitude stars selected from the *Palomar-Green Survey*. The data include photometric magnitudes accurate to ≤ 0.01 mag in most cases, plus colours and the reddening free $[c_1]$ and $[u-b]$ indices, which possess a precision of better than 0.02 and 0.04 mag, respectively. The latter should be suitable for the reliable determination of stellar photometric temperatures.

Key words: stars: early-type – stars: fundamental parameters – Galaxy: halo

1. Introduction

Despite detailed studies for more than two decades, the evolutionary status of hot stars at high Galactic latitudes remains unclear. Previously, we have identified individual objects which are spectroscopically similar to normal Population I stars at distances from the Galactic plane (*z*) of up to 25 kpc (Little et al. 1995). However, many advantages are offered by the observation of a complete magnitude limited sample. This would permit the determination of the total number of normal stars and their distribution as a function of *z*-distance and mass/spectral type. For stars which have been formed in the Galactic halo, their evolutionary ages together with their number density will permit us to estimate their formation rate, which can then be compared with current theories (Christodoulou et al. 1997). For stars which have been formed in the disc, we will be able to distinguish between ejection hypotheses, such as gravitational interactions within stellar clusters or supernova explosions, which predict differing stellar properties (eg. stellar abundance anomalies).

We have observed a sample of 205 stars in a 3 600 degree^2 region of sky selected from the *Palomar-Green Survey* (Green et al. 1986). The latter contains all objects brighter than B=16.1 over a 10 714 degree^2 area of sky with Galactic latitudes, $|b| \geq 30°$. Intermediate resolution spectra (∼4 Å FWHM) were obtained on the 4.5-m Multi-Mirror Telescope and 2.3-m telescope at the Steward Observatory. A subsequent analysis of the H I and He I absorption line-spectra eliminated the high gravity subdwarf/blue horizontal branch stars (sdB/BHB), leaving a subset of 57 stars with $B \leq 15.6$ and $\log g \leq 4.5$. Although typical for normal Population I B-type stars, such gravities are also comparable with evolved objects, particularly post-BHB and post-Asymptotic Giant Branch (PAGB) stars. These evolved objects exhibit near Population I abundances for some elements (Hambly et al. 1996, and references therein), but they do not display normal abundance patterns (as compared to young B-type stars) for all elements. Hence, it is possible to differentiate between the different evolutionary phases by undertaking a detailed abundance analysis using high spectral resolution data (Hambly et al. 1996).

In order to undertake a detailed model-atmosphere analysis, we require an accurate measure of the stellar effective temperature ($T_{\rm eff}$). This can be achieved from high-resolution spectroscopy using, for example, the Si II / Si III ionisation balance together with the Si II 4128 and Si III 4552 Å line strengths. However, this method may give rise to some problems, (i) unreliable $T_{\rm eff}$ values may be obtained since the Si II line-strength calculations can be subject to large non-LTE effects (Ryans et al. 1996), (ii) weak Si II and Si III line profiles can be smeared out by the large rotational velocities often associated with normal B-type stars, or (iii) in evolved stars, possible element deficiencies may make the Si II and Si III lines difficult to measure. Alternatively, reliable photometric temperature estimates can be derived using Strömgren *uvby* photometry. The subsequent model-atmosphere analyses performed on the stellar spectra will permit determination of stellar surface gravities, along with luminosities and distances, from the hydrogen line profiles. In addition, metal-lines will provide stellar chemical compositions allowing us to distinguish Population I stars from evolved objects. Our magnitude-limited survey will enable us to determine both number densities and spatial distributions for Population I and Population II stars. For the latter, these parameters will advance our understanding of the nature of blue halo stars, and in particular, the contribution of evolved field stars to the UV radiation phenomenon, viz. the UV upturn in elliptical galaxies and galaxy bulges (Dorman et al. 1995).

2. Observations and data reduction

The photometric measurements were performed using the 1.0-m Jacobus Kapteyn Telescope + 1k × 1k TEK CCDs (giving a

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Table 1. Zero-points, extinction co-efficients and colour terms

Run	Night	Zero-Point				Extinction Co-efficient				Colour Term			
		u_1	v_1	b_1	y_1	u_2	v_2	b_2	y_2	u_3	v_3	b_3	y_3
24 - 26 Dec 1996		3.490	3.003	2.569	2.891	0.490	0.250	0.160	0.106	-0.010	-0.060	-0.090	-0.040
16–25 Aug 1997	1	4.057	3.560	3.122	3.488	0.546	0.272	0.187	0.132	0.041	-0.036	-0.080	-0.054
	2	4.056	3.549	3.134	3.488	0.520	0.271	0.170	0.129	”	”	”	”
	3	4.088	3.545	3.122	3.503	0.535	0.296	0.183	0.117	”	”	”	”
	4	4.141	3.531	3.120	3.492	0.523	0.299	0.191	0.139	”	”	”	”
	5	4.093	3.509	3.123	3.495	0.551	0.311	0.184	0.135	0.041	-0.036	-0.080	-0.054
	6	4.120	3.532	3.166	3.534	0.548	0.304	0.159	0.111	”	”	”	”
	7	4.096	3.512	3.117	3.503	0.548	0.296	0.176	0.118	”	”	”	”
	8	4.176	3.544	3.121	3.510	0.502	0.270	0.182	0.120	”	”	”	”
	9	4.144	3.509	3.108	3.499	0.536	0.290	0.185	0.127	0.041	-0.036	-0.080	-0.054
07 -09 Feb 1998		4.287	3.925	3.484	3.809	0.510	0.282	0.171	0.115	0.043	-0.083	-0.088	-0.052

useful sky coverage of 5.6×5.6 arcmin) and *uvby* filter set at the Isaac Newton Group of Telescopes, La Palma, during the periods 24–26 December 1996, 16–25 August 1997 and 07–09 February 1998. For a typical target with B=15, integration times were 600:150:60:60 seconds through the $u : v : b : y$ pass-bands respectively. This provided approximately 10 000 counts/pixel in each pass-band giving a photometric accuracy of $\simeq$0.01 magnitudes. Furthermore, three independent observations were imaged per filter per object, which facilitated the removal of cosmic ray events using median filtering algorithms, and improved the photometric accuracy of the dataset. Bias calibration and sky flat-field frames were obtained at the beginning and end of each night. Standard stars were observed close to zenith during evening and morning twilight, thus allowing an in-depth determination of the instrumental colour transformation to the standard system. In addition, two standard stars were photometered at regular intervals throughout the night, at airmasses close to the programme stars, for the determination of extinction co-efficients and zero points. All stars used to standardize the instrumental magnitudes were previously observed by Stetson (1991).

Initial CCD reductions were performed using the IRAF CCDRED package (Massey 1992), where further details of the procedures can be found. This involved trimming the data section and subtraction of the mean overscan level, combining bias frames and correcting for any 2-dimensional structure in the residual bias level where necessary, and flat-fielding the CCD frames.

3. Photometric analysis

Subsequent photometry of the standard stars was performed using tasks within the IRAF package DAOPHOT (Massey & Davis 1992, Davis 1994). Instrumental magnitudes for the standard stars were determined using aperture photometry techniques, where for each night we have adopted an optimum aperture radius to which all photometric measurements for that night are referred. The choice of an optimum aperture radius is constrained by two competing effects: 1) Although larger apertures include more starlight, the increased contribution from the sky background results in a deterioration of the signal-to-noise ratio. Furthermore, the effects of cosmic ray events and bad pixels will become more significant. 2) Small apertures provide the best signal-to-noise ratio but both the seeing and telescope focus will dominate the stellar profile, resulting in possible inconsistencies between different CCD frames. The optimum aperture size was determined empirically by computing the instrumental magnitudes of all the standard star observations for a range of digital radii. Throughout the August 1997 run we typically encountered stellar profiles with a full-width-half-maximum (FWHM) of 3–4 pixels. Using $\sim$15 standard star observations per night, we deduced that the benefits of including a greater fraction of the total starlight through larger apertures was balanced by the increasing photometric errors for an aperture radius that was approximately 6 times the FWHM of the stellar profile. Aperture sizes were determined on a nightly basis rather than over the entire run. For the December 1996 and February 1998 runs, stellar profiles of 5–6 pixels FWHM were observed on all nights, and an aperture radius that was 6 times the FWHM was employed for both datasets.

The instrumental magnitudes were transformed to the standard system using equations of the form

$m_u = u + u_1 + u_2\, X_u + u_3\, (u - v)$
$m_v = v + v_1 + v_2\, X_v + v_3\, (v - b)$
$m_b = b + b_1 + b_2\, X_b + b_3\, (b - y)$
$m_y = y + y_1 + y_2\, X_y + y_3\, (b - y)$

where m_u, m_v, m_b, and m_y are the instrumental magnitudes, u, v, b and y the standard magnitudes, X_i (with $i = u, v, b, y$) the airmass and $u_{1...3}$, $v_{1...3}$, $b_{1...3}$ and $y_{1...3}$ are the transformation coefficients. The transformation equations were solved using tasks within the IRAF package PHOTCAL (Massey & Davis 1992). Solutions of the zero-points, extinction coefficients and colour terms for each of the runs are listed in Table 1. For the December 96 and February 98 observations, mean transformation co-efficients were evaluated for each dataset, whereas during the August 97 run, zero-points and extinction co-efficients were determined on a nightly basis and an average colour term was adopted for the nine nights. For the latter run, standard deviations of the aforementioned co-efficients in the y pass-band were

Table 2. Strömgren photometry of the programme stars

Star ID	α (J2000.0)	δ (J2000.0)	y	$(y)_e$	$(b-y)$	$(b-y)_e$	m_1	$(m_1)_e$	c_1	$(c_1)_e$	$[c_1]$	$([c_1])_e$	$[u-b]$	$([u-b])_e$
PG0009+036	00 12 28.00	+03 54 30.0	13.164	0.005	-0.033	0.006	0.110	0.008	0.513	0.003	0.519	0.003	0.718	0.011
PG0011+283	00 14 22.00	+28 37 02.0	12.710	0.003	-0.099	0.005	0.101	0.005	0.117	0.027	0.137	0.028	0.275	0.015
PG0133+114	01 36 26.00	+11 39 30.0	12.315	0.011	-0.079	0.020	0.074	0.035	0.050	0.014	0.065	0.011	0.163	0.048
PG0823+499	08 27 36.00	+49 45 36.0	12.053	0.006	-0.069	0.009	0.129	0.025	0.271	0.025	0.285	0.024	0.500	0.029
PG0848+186	08 51 44.00	+18 27 24.0	13.278	0.009	-0.086	0.008	0.106	0.022	0.306	0.029	0.323	0.028	0.481	0.012
PG0853+019	08 56 11.17	+01 40 37.6	9.237	0.003	-0.126	0.003	0.069	0.003	0.069	0.007	0.094	0.007	0.152	0.005
PG0855+294	08 58 21.00	+29 12 12.0	12.306	0.006	-0.110	0.017	0.151	0.029	0.141	0.014	0.162	0.010	0.396	0.039
PG0914+001	09 17 12.00	-00 08 36.0	14.583	0.028	-0.065	0.036	0.101	0.061	0.730	0.018	0.743	0.012	0.903	0.089
PG0936+109	09 39 35.20	+10 43 18.0	14.213	0.008	-0.054	0.010	0.109	0.006	0.520	0.034	0.530	0.036	0.715	0.019
PG0955+291	09 58 14.40	+28 52 26.0	13.010	0.004	-0.053	0.006	0.090	0.003	0.594	0.019	0.605	0.020	0.751	0.011
PG1011+293	10 13 56.02	+29 06 20.0	14.002	0.033	-0.003	0.033	0.062	0.023	0.563	0.022	0.563	0.028	0.685	0.047
PG1205+228	12 07 57.40	+22 31 47.0	11.033	0.001	-0.060	0.004	0.079	0.012	0.380	0.006	0.391	0.005	0.510	0.017
PG1209+263	12 12 12.90	+26 00 02.0	14.583	0.013	-0.008	0.017	0.102	0.045	0.766	0.052	0.767	0.049	0.966	0.042
PG1332+137	13 35 11.98	+13 27 44.1	11.878	0.003	-0.070	0.009	0.081	0.017	0.398	0.013	0.412	0.012	0.529	0.016
PG1400+389	14 02 09.10	+38 37 19.0	12.203	0.004	-0.080	0.006	0.092	0.014	0.311	0.015	0.327	0.015	0.459	0.015
PG2103+021	21 05 46.90	+02 16 29.0	15.538	0.021	0.005	0.022	0.063	0.041	0.370	0.049	0.369	0.047	0.497	0.035
PG2111+023	21 13 42.40	+02 33 09.0	13.288	0.002	-0.040	0.017	0.121	0.036	0.470	0.032	0.478	0.030	0.694	0.041
PG2120+062	21 22 31.70	+06 21 54.0	14.398	0.008	0.005	0.018	0.027	0.028	-0.042	0.025	-0.043	0.022	0.013	0.024
PG2128+146	21 31 18.80	+14 49 26.0	13.218	0.011	-0.013	0.016	0.103	0.017	0.507	0.012	0.510	0.014	0.708	0.034
PG2132+126	21 34 55.00	+12 49 21.0	14.907	0.015	0.007	0.022	0.100	0.029	0.420	0.023	0.419	0.019	0.624	0.026
PG2134+049	21 36 40.40	+05 08 02.0	14.220	0.007	0.009	0.007	0.062	0.012	0.420	0.019	0.419	0.020	0.548	0.026
PG2146+087	21 48 57.00	+08 53 03.0	14.257	0.005	0.011	0.003	0.092	0.003	0.204	0.003	0.202	0.004	0.393	0.004
PG2159+051	22 01 51.00	+05 22 16.0	12.983	0.005	0.006	0.016	0.094	0.029	0.449	0.027	0.448	0.025	0.639	0.032
PG2209+192	22 12 14.70	+19 25 19.0	14.663	0.005	-0.071	0.011	0.068	0.017	0.221	0.054	0.236	0.053	0.326	0.032
PG2212+027	22 14 38.00	+02 57 14.0	15.606	0.007	-0.010	0.016	0.102	0.029	0.241	0.019	0.243	0.019	0.441	0.049
PG2214+184	22 17 04.30	+18 37 55.0	14.262	0.012	-0.059	0.021	0.131	0.037	0.391	0.032	0.402	0.032	0.626	0.062
PG2219+094	22 21 59.10	+09 37 31.0	11.955	0.005	-0.043	0.007	0.089	0.008	0.337	0.003	0.345	0.003	0.496	0.013
PG2237+178	22 39 53.30	+18 02 46.0	14.875	0.019	-0.031	0.033	0.115	0.043	0.555	0.023	0.561	0.022	0.771	0.065
PG2336+004	23 38 43.60	+00 42 55.0	15.894	0.022	-0.060	0.032	0.094	0.046	0.184	0.049	0.196	0.044	0.344	0.041
PG2351+198	23 53 45.00	+20 06 09.0	14.063	0.008	-0.009	0.005	0.114	0.019	0.417	0.020	0.419	0.020	0.641	0.019
PG2356+167	23 59 25.10	+16 56 42.0	14.223	0.017	-0.046	0.015	0.074	0.009	0.178	0.006	0.187	0.007	0.307	0.011

Table 3. Comparison with previous photometry

Star ID	y	$(b-y)$	m_1	Ref
PG0009+036	13.155	-0.048	0.099	1,2
	13.138 ± 0.007	-0.035 ± 0.003	0.104 ± 0.002	3
PG0011+283	12.762 ± 0.079	-0.114 ± 0.017	0.100 ± 0.003	2
PG0133+114	12.280 ± 0.023	-0.087 ± 0.005	0.094 ± 0.008	3
	12.345	-0.099	0.096	2
PG0848+186	13.253 ± 0.024	-0.078 ± 0.025	0.100 ± 0.030	2
PG1400+389	12.161 ± 0.005	-0.071 ± 0.001	0.106 ± 0.005	2
PG2111+023	13.249	-0.028	0.086	2
PG2120+062	14.398 ± 0.029	-0.018 ± 0.034	0.058 ± 0.031	2
PG2128+146	13.216	-0.035	-0.095	2
PG2159+051	12.984	-0.021	0.100	2
PG2214+184	14.242	0.002	0.047	2
PG2219+094	11.915 ± 0.005	-0.055 ± 0.008	0.110 ± 0.003	1,3
PG2356+167	14.209 ± 0.006	-0.070 ± 0.004	0.107 ± 0.014	2

References: (1) Rolleston et al. (1999); (2) Wesemael et al. (1992); (3) Moehler et al. (1990)

of the order of 0.014, 0.009 and 0.006 magnitudes respectively, suggesting stable atmospheric conditions throughout.

Of the three transformation coefficients, colour terms are the most difficult to procure. However, colour terms derived independently for each night of the August 97 run were in good agreement. This is to be expected since the instrumental set-up was not changed during the run; hence, our justification for adopting mean values. The same method was applied to the December 96 and February 98 observations, but as each dataset contained only two nights of useful data, errors in the derived colour terms were considerably larger. However, comparison of all three datasets demonstrates reasonable agreement, and in all cases colour terms agree to within the errors. As the same instrumental set-up was used during all three runs, there is no reason to believe that the colour terms will differ, and so we have adopted the mean August 97 colour terms in the analysis of all three data sets.

Aperture photometry was again undertaken for the target stars (using the optimum aperture radius as derived from the standard stars), with the exception of PG 2103+021 for which point-spread function (PSF) photometry was necessary. The latter was employed in order to account for contaminating starlight from close neighbours in the field. Independent PSF's were calculated for each CCD frame which were then used to calculate instrumental magnitudes. An aperture correction was then applied to account for the smaller fitting radius adopted in the PSF photometry compared to the large digital apertures used for the standard stars. Further details of this procedure can be found in Massey & Davis (1992).

4. Results and discussion

Strömgen photometry of the 31 programme stars is listed in Table 2. For all objects, we obtained a minimum of three independent sets of $uvby$ measurements. These were combined to give the mean magnitudes and colours that are presented in Table 2, where the quoted error represents the standard deviation of the mean value. In most cases we have achieved our desired photometric accuracy of $\simeq$0.01 magnitudes. To demonstrate repeatibility / reliability, repeat observations were performed during the same run and over separate runs. PG2351+198 was observed both in December 96 and August 97 and PG0936+109 was observed in December 96 and February 98. In both cases colours and magnitudes are in excellent agreement to within 0.010 and 0.005 mag respectively.

Table 4. Stellar effective temperature estimates (K)[a]

Star ID	$T_{\rm eff}$ (K)		δ
	[c$_1$]	[u-b]	
PG0009+036	13 900	13 800	100
PG0011+283	21 100	20 800	300
PG0133+114	23 300	23 400	100
PG0823+499	17 500	16 400	1100
PG0848+186	16 800	16 800	0
PG0853+019	22 400	23 700	1300
PG0855+294	20 500	18 300	2200
PG0914+001	11 900	12 400	500
PG0936+109	13 800	13 900	100
PG0955+291	13 000	13 500	500
PG1011+293	13 400	14 000	700
PG1205+228	15 600	16 300	700
PG1209+263	11 800	12 000	200
PG1332+137	15 300	16 000	700
PG1400+389	16 700	17 100	400
PG2103+021	15 900	16 500	600
PG2111+023	14 400	14 100	300
PG2120+062	27 800	28 200	400
PG2128+146	14 000	13 900	100
PG2132+126	15 200	14 900	300
PG2134+049	15 200	15 800	600
PG2146+087	19 400	18 400	1000
PG2159+051	14 800	14 700	100
PG2209+192	18 600	19 700	1100
PG2212+027	18 500	17 400	1100
PG2214+184	15 400	14 800	600
PG2219+094	16 300	16 500	200
PG2237+178	13 500	13 400	100
PG2336+004	19 600	19 300	300
PG2351+198	15 200	14 600	600
PG2356+167	19 800	20 000	200

[a] Determined assuming a typical main-sequence gravity of $\log g = 4.0$.

We have also undertaken a literature search for published Strömgren photometry of stars in common with our sample. In Table 3, we present previous measurements for twelve stars. A comparison with our photometry yields a mean difference in the y magnitudes and colours of approximately 0.025 mag. However, previous studies were often based on only one set of $uvby$ measurements, and the photometric errors in y were on average greater than 0.02 magnitudes. Hence, we believe our new photometry to be more reliable as colours and magnitudes should be accurate to better than 0.02 and 0.01 magnitudes respectively.

Lastly, we have investigated the suitability of this photometry to determine stellar effective temperatures. It should be noted that effective temperatures derived from Strömgren photometry depend on the stellar surface gravity. Hence, final effective temperatures can not be deduced for our stellar sample until the hydrogen-line spectra have been obtained. However, as a self-consistency check, we derived temperature estimates using the $[c_1]$ and $[u-b]$ reddening free indicies and the calibrations of Lester et al. (1986) for a typical main-sequence logarithmic surface gravity of $\log g = 4.0$ and a solar composition, and these are shown in Table 4. Comparison of the two sets of temperatures provides excellent agreement for all stars, with a mean difference of $\sim$500 K. Furthermore, the temperatures are consistent with their spectral types based on low-resolution spectroscopy (Saffer et al. 1997). Therefore, we anticipate that our photometry should provide reliable photometric temperature estimates.

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