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ASTRONOMY AND ASTROPHYSICS

Proper motions of the hot subdwarfs

The kinematic population membership of the sdB*

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Abstract. **We report on first results from an ongoing program to measure and analyze proper motions for hot subdwarf and white dwarf stars, with the aim of determining to which stellar population sdB stars (in the V magnitude range 10.5 to 14.5) belong. Ours is the largest sample of hot subdwarf proper motions measured to date. Our kinematic analysis suggests that the parent population of these hydrogen-rich sdB stars is as old or older than the old disk. We measure the absolute magnitude of the sdB in the field as M_V = 4.5, providing independent confirmation of absolute V magnitude estimates for these stars from clusters and spectroscopic analyses.

Provided it can be shown that the sdO stars evolve from the sdB, then the sdO absolute V magnitude distribution is about 1 magnitude brighter than for the sdB, and 1 magnitude wider.

Key words: astrometry – stars: subdwarf – fundamental parameters – Galaxy: stellar content

1. Introduction

The hot subdwarf stars are found in the Color-Magnitude diagram on and above the very blue end of the horizontal branch, and are seen both in the field and cluster populations. The hydrogen rich subdwarf B (sdB) stars lie *on* the extended blue horizontal branch (EHB) and are currently identified with the helium-core burning stage of stellar evolution. The neighboring (sdO) stars lie *above* the EHB and are not as well understood. Beyond knowing that the sdO are hot (40,000K to 80,000K) and helium-rich (photospheres are 10% to 100% He, by number), little else is accurately known. The surface gravity, found in NLTE spectral analysis, is known to lie in the range log(g)=5.0 to 7.0. Theories for the formation and evolution of sdB and sdO stars fall in several categories based on whether they involve single star evolution or require binary scenarios. Canonical single star evolution theory, in the form of model evolution calculations (e.g. Caloi 1989) describes the sdB stars as evolving into sdO stars. One test of this is whether the spatial kinematics for sdB and sdO stars are similar. We are engaged in a large project to collect such data, but before we can analyze the proposition we have to focus on an important sub-problem – namely that of determining the population membership of the sdB stars themselves. This is important because the sdB stars are better understood than the sdO and have more complete data available, which makes an analysis possible now. Progress on the sdO will require solution of various problems related to difficulties in spectral analysis and in gathering kinematical data for enough sdO stars – there are not very many sufficiently bright sdO stars known, compared to the large number of sdB stars. We have gathered kinematical data for the sdB test and report on the results of a simple analysis of these in this paper.

We also attempt to estimate the absolute magnitude of the sdB, since this can be used to set limits to the sdB mass. Since all spectroscopic analyses of field sdB stars have used the assumption of a typical EHB stellar mass near 0.5 $M_\odot$ in order to derive the absolute magnitude from atmospheric parameters, for the first time we can test this assumption from field stars. For cluster sdB stars, other possibilities exist for analysis, due to the (in principle) known distance to the cluster, but separate problems exist in interpreting the cluster sdB data (see Moehler et al. 1995, for a review of this problem).

Reviews of the hot subdwarf literature and summaries of the present knowledge of these objects can be found in Heber (1986, 1992), Saffer&Liebert (1994) and Thejll (1995), and references therein.

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* Based on observations made with the Carlsberg Automatic Meridian Circle operated on the island of La Palma by the Copenhagen University Observatory, Royal Greenwich Observatory and Real Instituto y Observatorio de la Armada en San Fernando.

** The Tables 5 to 11 are only available in electronic form at the CDS via anonymous ftp 130.79.128.5 or http://cdsweb.u-strasbg.fr/Abstract.html.

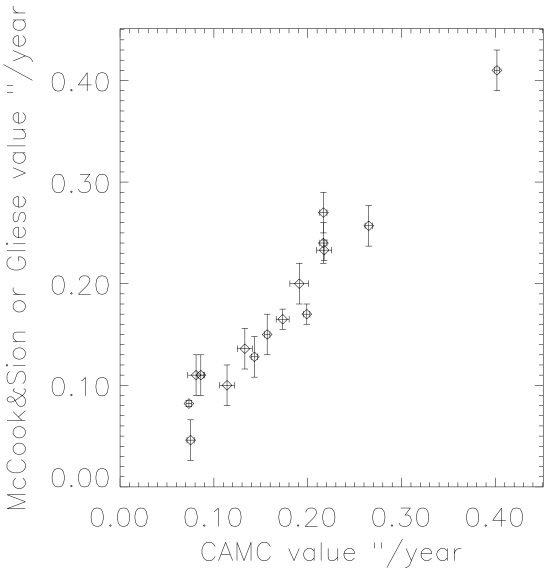

Fig. 1. Comparison of white dwarf proper motions. The errors for the comparison proper motions was set at 0.02 "/year (Jahreiß, private communication, 1995).

2. Observations

Positions of 348 white dwarfs (WD), hot subdwarf B and hot subdwarf O (sdB and sdO) stars were measured with the Carlsberg Automatic Meridian Circle (CAMC) on La Palma during the period 1987 - 1993. The positions will be published elsewhere (CAMC Catalogues, 4 - 9). Of these stars, 100 sdB, 28 sdO, and 18 WDs could be found in the Astrographic Catalog and proper motions calculated. The typical error in the proper motions is quite small, 0.005 arcsec yr^{-1}, and it is this high accuracy which makes the measurement of the kinematics of the subdwarf stars feasible. Our results are shown in Tables 4–9 for hot subdwarfs and Tables 10–11 for white dwarfs[1].

For 15 of our WDs proper motions exist in the literature (McCook&Sion 1987, and Gliese&Jahreiß 1991) and we compared these to our new measurements in Fig. 1. The agreement is very satisfactory. Note that our new data are much more accurate than the previously measured proper motions for these objects, which typically have errors of approximately 0.02 arcsec yr^{-1}.

It was also possible to calculate proper motions using the Guide Star Catalog (GSC) and the digitized version of the Palomar Observatory Sky Survey (POSS) for 23 stars. For those 17 targets that also have CAMC-AC derived proper motions we performed a comparison of the size of the proper motion and the position angle, and found satisfactory agreement.

For some of our objects the best available celestial coordinates were of low accuracy, so that it was uncertain if we had recovered the correct object with the CAMC, particularly in crowded fields. In all cases however, it was possible to check the measured object by working backward from the CAMC photometry and coordinates. First, we checked that the photometry was consistent with data in the literature, where available, and furthermore that the object was the singularly blue object in the field (using finding charts constructed from the APM two colour digitized POSS available via the Internet.) All objects were tested in this way and a small number of erroneous targets were weeded from our final lists.

[1] For availability, please see footnote 1 in the Abstract

3. Estimating the sdB kinematics and population type

Normally, to derive the kinematics and hence population type of a group of stars from proper motion or radial velocity data, and for which the absolute magnitude is unknown or uncertain, statistical parallax methods are used. Statistical parallax usually relies on a good distribution of the stars around the sky, which is certainly not the case for these small samples. Below we introduce a Monte Carlo technique which circumvents this problem, by simulating what we would expect to observe in small samples of stars drawn from one of four representative populations in the Galaxy.

We begin by analysing the stars for which we have radial velocities, since the kinematic information is in this case independent of distance. Saffer (1991) has measured radial velocity (RV) data for 31 sdB, and for 11 of his sdB we have now measured proper motions. For the 31 sdB, the dispersion of the line-of-sight velocities is $\sigma_{\rm los} = 40 \pm 5$ km s^{-1}, while for the 11 sdB with proper motions as well, the dispersion is $\sigma_{\rm los} = 42 \pm 9$ km s^{-1}. (We have corrected these velocity dispersions by subtracting quadratically the quoted measuring errors in the radial velocities).

Let us first assume that these stars belong to one of four representative populations in the Galaxy, either the young disk (age less than about a Gyr), the old disk, the thick disk or the halo (see Freeman 1989 for a review of the properties of these populations). The kinematic properties (velocity ellipsoid $(\sigma_U, \sigma_V, \sigma_W)$ and asymmetric drift, $V_{\rm ass}$) of these four groups are well known, and are shown in Table 1. Consider now a small sample of N stars, drawn from one of these populations, at positions on the sky (α_i, δ_i) for $i = 1 \ldots N$. We carry out a large number of Monte Carlo simulations in which N objects at these positions on the sky are drawn from one of the representative stellar populations above. A space motion (U, V, W) directed along the usual Galactic coordinates (X, Y, Z) is randomly selected for each of the N objects, from a Gaussian distribution with dispersions $(\sigma_U, \sigma_V, \sigma_W)$ and mean $(U, V, W) = (0.0, -V_{\rm ass}, 0.0)$ from which line of sight velocities can be computed. The dispersion of the line of sight velocities is then calculated (for a large number of simulations to smooth out statistical variations) for each of the representative populations, and compared to this quantity for the real stars. Further, if the apparent magnitude for each star is known in the actual sample, then for a given assumed mean absolute magnitude for the stars a distance along each line of sight in the Monte Carlo simulations can be assigned, and hence the expected distribution of proper motions can be simulated as well, and compared to the observations.

Table 2 gives the results for 2 samples of sdB stars – one being for those 31 sdB stars that Saffer gives RV data for (2

Table 1. Model population velocity dispersions in km s^{-1}. From Mihalas and Binney (1981).

	Young disc	Old disc	Thick disc	Halo
σ_U	20	40	80	150
σ_V	15	30	60	90
σ_W	10	20	40	90
V_{ass}	−10	−20	−40	−220

Table 2. Table of radial velocity dispersions (in km s^{-1}) for two samples of sdB stars and the four model populations.

observed sdB σ_{los} km s^{-1}	40±5	42±9
Number of objects	31	11
model Young disk	15	15
model Old disk	30	29
model Thick disk	63	61
model Halo	151	143

stars have been excluded as their velocities are so great that they are clearly interlopers from the halo), and the other being those 11 sdB stars for which we also have proper motions (PG0250+189, PG0342+026, PG0749+658, PG0918+029, PG0919+272, PG1114+072, PG1224+671, PG1230+052, PG1325+101, PG1704+221, PG2204+034). From the table one can see that the observed line of sight velocity dispersion indicates that our sdB sample comes from a population which is midway between the old disk and the thick disk.

For 11 of the sdB we have RV and proper motions, so for these stars we can calculate the space velocities of each star for an assumed mean absolute magnitude of the sdB. If we again assume that the stars belong to one of the four population types above, then the expected distribution of space velocity can be simulated for our small sample, and compared to the actual observations. Of course, since the space velocities derived depend on the distance via the two observed proper motions but are independent of the observed radial velocity, we can recover an estimate of the sdB absolute magnitude in this way.

If we assume for simplicity no intrinsic scatter in the absolute magnitudes of the sdB, then the best match between the space velocities we derive for the 11 stars and the space velocities of a large number of 11-star samples drawn from the Monte-Carlo simulation is for $M_V = 4.8$ with an error of ±0.5. The sdB may actually have an intrinsic scatter in their absolute magnitudes, which means that using a mean absolute magnitude for each of the 11 stars in order to derive the space velocities will artificially increase the dispersion of their space velocities. We examine this in more detail in the next section.

The absolute V magnitudes of sdB have been established by Heber (1986) ($M_V = 4.2 \pm 0.7$,), and a similar result ($M_V = 4.5 \pm 1$) is derivable from the larger work by Saffer (1991) if Bolometric Corrections (from Kurucz (1993) atmospheric models) are used and absolute magnitudes calculated from the atmospheric parameters and the assumption of a 0.5 $M_\odot$ mass.

Table 3. Results of fitting the H-distribution for sdB.

	Young disc	Old disc	Thick disc	Halo
M_V(sdB)	6.5	5.0	3.6	1.2
σ_{M_V}(sdB)	0.7	0.8	0.8	1.2

We find there is good agreement between the observed absolute magnitudes and the one derived above from kinematics alone – this is the first confirmation of its kind and lends support to the assumption of the 0.5 $M_\odot$ mass. This support was previously only present from the comparison of theoretical EHB evolution tracks to observed atmospheric parameters.

4. The H distributions of sdB and sdO

We turn now from the small set of stars that both have known radial velocities and proper motions, to the larger set of stars that have known proper motions only.

To examine the relative population memberships of sdB and sdO we compared the reduced proper motions (Jones 1972) $H = m + 5log\mu + 5 = M + 5logT$, where m and M are the apparent and absolute magnitudes, respectively, μ is the proper motion in " yr^{-1} and T the tangential velocity in AU yr^{-1}. The resulting H distributions are seen in Fig. 2.

Formally, the statistical significance of the different distributions of H is evaluated using Student's t test for distributions with possibly different variances. The probability that the two distributions have the same mean is found to be 0.0016 which we interpret as significant evidence that the two distributions of H are different. The χ^2-test gives the probability that the two distributions of H are drawn from the same parent distribution – this has a probability of about 9%, calculated using the method in Press et al. (1992; Sect. 14.2). This also supports the idea that the sdB and sdO H distributions are different, although less stringently.

The distributions of H reflect both the velocity ellipsoid of the stars, the mean absolute magnitude of the stars as a group, and, importantly, the scatter in their absolute magnitude. To examine the H distributions further, we again assume that the stars belong to one of the four Galactic populations above, and calculate the expected H distribution for various assumptions about the mean absolute magnitude and scatter in absolute magnitude of the sdB and sdO.

As before, the stars are not optimally spread around the sky, but are in fact somewhat concentrated towards the galactic poles. We remove this bias as before by drawing stars from our simulated samples along the same lines-of-sight as in the observed sample.

We consider first the sdB because their absolute magnitude is more secure than the sdO.

A large number of simulations, over a grid in mean absolute magnitude M_V(sdB) and intrinsic scatter in the sdB absolute magnitude σ_{M_V}(sdB), were run in order to smooth out statistical variations. For each of the four populations, the expected H distribution was simulated and compared to the H distribution of the real stars. The χ^2 statistic was calculated between the

Table 4. Hot subdwarf astrometry results. From the observations at the CAMC coordinates in epoch J2000.0 are given (coloumns 1-6). Proper motions have been calculated using the positions retrieved from the Astrographic Catalogue. Proper motions calculated by using a digitized version of the POSS, and the Guide Star Catalog are also given, when available. Double entries, such as for the star at (01 19 29.04 +24 25 31.86) gives first the values from the CAMC/AC and then secondly the GSC/POSS value. 7 stars in this table were only recoverable in the GSC/POSS system, and these are shown with the symbol (†) after the hh. Notes: a=PHL 678, b=PHL 2726=PB5795, c=PB6107, d=PHL 932, e=Feige 11=FB 13=PB 6252, f=Feige 19=PB 6715, g=TON 13=FB 55, h=GD299=FB 57, i=GD300=FB60, j=UVO1032+40=PB 385, k=Feige 34=FB 64=PB 462, l=TON 1273, m=TON 1281, n=LB1938, o=Feige 36, p=Feige 38, q=TON 1384, r=EG 81=Feige 46, s=PB3854, t=HZ 22, u=Feige 65, v=BD+18 2647, w=BD−7 3477=HW Vir, x=TON 139, y=HZ 38, z=LB27, aa=Feige 80, ab=Feige 87, ac=PB1207, ad=TON 183, ae=TON 194, af=Feige 95, ag=TON 209, ah=UVO1505+07, ai=TON 788, aj=TON 803, ak=LB9514, al=Feige 109, am=PB5333, an=GD314, and ao=GD108. The remainder of the tables of hot subdwarf astrometric data (Tables 5–9) is available at the CDS only (see footnote to the abstract).

hh	mm	ss.ss	deg	min	sec	μ	θ
						err.	err.
0	1	6.73	+11	0	36.32	.0143	192.
						.0035	28.
0	7	33.77	+13	35	57.65[a]	.0252	173.
						.0043	11.
0	12	27.77	+03	54	31.60[b]	.0076	23.
						.0039	56.
0	14	19.32	+22	24	17.61	.0034	126.
						.0040	48.
0	14	22.24	+28	36	55.96	.0222	187.
						.0034	16.
0	35	32.04	+24	59	15.95	.0155	105.
						.0034	17.
0	42	6.11	+05	9	23.37[c]	.0141	148.
						.0041	8.
0	42	16.58	+13	45	40.49	.0042	224.
						.0059	70.
0	59	56.65	+15	44	13.57[d]	.0393	97.
						.0032	8.
1	4	21.67	+04	13	37.26[e]	.0418	163.
						.0037	6.
1	5	22.40	+26	22	54.07	.0095	276.
						.0030	2.
1	13	14.87	+26	27	31.18	.0060	276.
						.0020	15.
1	15	54.26	+26	14	00.23	.0034	53.
						.0039	79.
1	19	29.04	+24	25	31.86	.0992	176.
						.0022	3.
						.088	177.
						.009	6.

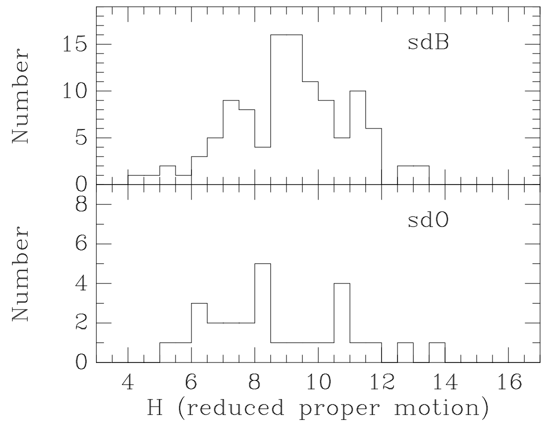

Fig. 2. Reduced proper motions H for our sample of hot subdwarfs. $H = m{+}5log\mu{+}5 = M{+}5logT$, where m and M are the apparent and absolute magnitudes, respectively, μ is the proper motion in $''/year$ and T the tangential velocity in $AU/year$.

observed and model H distributions and the best fitting models found by minimizing this quantity. The results are shown in Table 3.

As expected, the data could be well fitted for all four populations, by adjusting the mean absolute magnitude appropriately. However, since we know independently from the radial velocity analysis above that the sdB must be intermediate between old disk and thick disk in their kinematics, from this we estimate that the mean absolute V magnitude of the sdB is M_V(sdB) = 4.5, with an intrinsic scatter in their absolute magnitude of 0.8 mag.

We have performed a similar analysis of the 28 sdO stars in our data. In this case, we are hampered significantly by not knowing the population type of the objects, essentially through having no radial velocity data. We can express our results relative to the sdB, however. We find that *if* the sdO stars are from the same kinematic population as the sdB (as would be the case in a scenario where sdB stars evolve to sdO stars) *then* the mean absolute magnitude of the sdO stars is 1.0^m brighter than the sdB and the intrinsic scatter in the absolute V magnitudes 1.0^m greater. These numbers have statistical errors of the order of 0.2^m, dominated by the effect of the smaller number of sdO. A significantly larger scatter in the sdO absolute magnitudes is very clearly indicated. This scatter is also seen when spectroscopically derived sdO temperatures and gravities are plotted using the assumption of a single mass (e.g. Thejll et al. 1994).

5. Summary and discussion

We have observed and analyzed the largest sample of hot subdwarf (sdB and sdO) proper motions to date. We presented first an analysis of the space velocities for that set of sdB stars which had previously published radial velocities combined with our new proper motions. We found firstly that the space velocities are similar to those of populations intermediate to the Old and Thick disks, and secondly using a modified statistical parallax technique that the absolute magnitude of the sdB is $M_{\rm V} = 4.8 \pm 0.5$. This is in good agreement with what is known about sdB absolute V magnitudes from other investigations, theoretical and observational (and this constitutes the first independent observational evidence from field stars). This indicates that the common assumption of a $0.5\ {\rm M}_{\odot}$ mass for the sdB is warranted.

We then examined a much larger data set of sdB and sdO for which we have our new proper motions only. We showed that the reduced proper motion distributions of sdB and sdO imply that the absolute magnitudes are different, or that the kinematics are different, or both. If the sdO follow from the sdB by simple single-star evolution, then the kinematics will be the same and then we can infer that the absolute V magnitude distribution of the sdO is about 1 magnitude brighter, in the mean, and 1 magnitude broader, than the sdB distribution. This prediction is open to experimental test when direct or indirect distances are found from trigonometric data (e.g. HIPPARCOS astrometric data), or analysis of non-interacting binary systems with hot subdwarfs, or interstellar absorption and reddening analysis of hot subdwarf spectral features.

A population origin in the old part of the Galaxy would support those evolutionary scenarios that require great age for the hot subdwarfs to form. Such scenarios include single star evolution with strong mass loss on the first ascent of the red giant branch, and such binary scenarios that act to coalesce orbiting stellar cores (He white dwarfs, really) on a long time scale.

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