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Letter to the Editor

Calibrating horizontal-branch stars with Hipparcos*

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Abstract. Parallaxes from the Hipparcos satellite allow for the first time to calibrate parameters of horizontal-branch (HB) like stars based on geometric distances. We present absolute magnitudes and luminosities for 8 such stars. Using $T_{\rm eff}$ and log g values available from the literature, we also can calculate the mass of the HB stars. We find an average value of $M_{\rm HB}$ = 0.38 $\pm$0.07 M$_\odot$ for stars with 7500< $T_{\rm eff}$ <9000 K, well below the value from stellar evolution theory, which predicts masses near 0.6 M$_\odot$. Recent investigations of HB stars in globular clusters indicated similarly low mass values. The likely cause for the discrepancy of the mass values lies in the low gravities derived from Balmer line profiles.

Key words: astrometry; stars: horizontal branch; stars: fundamental parameters; stars: evolution

1. Introduction

Stars having started on the main sequence with masses of a little less than the Sun up to a few solar masses will in the later phases of evolution turn into horizontal-branch (HB) stars. They become red giants, and a considerable amount of mass is lost through the stellar wind. After core He-ignition the star adjusts its structure, thereby contracting the remainder of the atmosphere, and the star enters a quiet phase as HB star. Depending on the amount of mass left in the hydrogen envelope, the star is very blue and subluminous (little envelope) like sdOB or sdB stars, or is rather red (heavy envelope) like RR Lyr or red HB stars. In the middle range the stars are of HB-B or HB-A type with spectra rather similar to those of main sequence late B to early A stars. In all cases the mass in the He core is according to evolution models about 0.5 M$_\odot$ and the envelope mass ranges form $<$ 0.04 M$_\odot$ (very blue stars) to up to 0.9 M$_\odot$ (very red stars), with the HBB and HBA stars having a total mass of 0.52 to 0.6 M$_\odot$. HB-like stars then further evolve from the Zero-age HB (ZAHB), becoming somewhat more luminous. Several models for HB-stars and their evolution have been developed (Sweigart & Gross 1976, Caloi 1989, Dorman et al. 1993). A general review of the topic is given by Renzini & Fusi Pecci (1988).

The accurate parallaxes now obtained with the Hipparcos project can be used to calibrate all the parameters characterising horizontal-branch stars. This is, of course, foremost the absolute magnitude. When other observational data for the same stars are included, the luminosity, the temperature, gravity, and the mass can be determined. These parameters must be mutually consistent. Any discrepancies will point at not well understood aspects of observation, interpretation, or theory.

The verification of the parameters is urgently needed. Moehler et al. (1995) and de Boer et al. (1995) found discrepancies for the mass of HB-like stars in globular clusters. In particular, fits of model Balmer profiles to the spectra of HB stars in NGC 6397 of 8500< $T_{\rm eff}$ <12000 K imply a mass near 0.40 M$_\odot$ (de Boer et al. 1995), which is 0.2 M$_\odot$ below that expected from theory of evolution.

In order to clarify the issue of the HB-star masses and to possibly resolve the contradiction between theory and reality, we have investigated some of the well studied field HB stars and some sdB stars. We selected the relevant stars from the Hipparcos Input Catalogue (HIC; Turon et al. 1992), and their basic data are given in Table 1.

2. Hipparcos data, parallaxes

The Hipparcos astrometric satellite (see Perryman & Hassan 1989, Perryman & Turon 1989, Perryman et al. 1989) has provided data on parallaxes based on positional measurements between 1990 and 1993 of stars present in the HIC. After the full reduction of all measurements, a typical internal r.m.s. error of the Hipparcos parallaxes (Kovalevsky et al. 1995) is 1.5 milli-arcseconds (mas) with a slight dependence on magnitude and ecliptical latitude. Comparison of Hipparcos results with

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* Based on data from the HIPPARCOS Astrometry Satellite

Table 1. Field Horizontal Branch stars: Hipparcos parallaxes and distances

Name		HIC	V	$B-V$	$E(B-V)$	Type	π	σ_π	d	d_{max},d_{min}	M_V	ΔM_V
							(mas)		(pc)			
CD	−38 222	3381	10.47	−0.17	–	sdB	3.07	1.73	325	705,210	+2.91	1.25
HD	4539	3701	10.27	−0.24	–	sdB	4.65	1.96	215	370,150	+3.61	0.90
HD	86986	49198	7.99	+0.12	0.03	HBA	3.78	0.95	265	355,210	+0.79	0.55
HD	109995	61696	7.62	+0.04	0.00	HBA	4.92	0.89	205	250,170	+1.08	0.40
HD	130095	72278	8.13	+0.08	0.10	HBA	5.91	1.08	170	205,145	+1.68	0.40
HD	139961	76961	8.85	+0.10	0.10	HBA	4.50	1.19	220	300,175	+1.81	0.60
HD	161817	87001	6.96	+0.16	0.02	HBA	5.81	0.65	170	195,155	+0.72	0.25
HD	205805	106917	10.21	−0.26	0.0	sdB	3.77	1.70	265	485,185	+3.09	1.00

V and $B-V$ are from the Hipparcos Input Catalogue (HIC); the reddening is from sources given with Table 2
ΔM_V given is only due to the uncertainty in the parallax

ground-based parallaxes has shown that systematic errors in the Hipparcos parallaxes are below 0.1 mas (Arenou et al. 1995).

The values for the parallaxes of the HB stars from the Hipparcos Catalogue (ESA, 1997) are given in Table 1, together with the relevant error estimates. Note that all values are given in milli-arcseconds. Parallaxes have been determined previously for only 3 of the presently investigated FHB stars (see the HIC) but they have such a large uncertainty that a comparison with the presented Hipparcos values is not useful.

3. The absolute magnitudes

The absolute magnitudes of the HB stars follow directly from $M_V = V - A_V - 5 \log d + 5$, in which the correction for interstellar extinction is $A_V = 3.1E(B-V)$. The absolute magnitudes are plotted in Fig. 1, defining the horizontal branch for Milky Way field stars. The diagram shows that theory and models are in good general agreement. Red clump HB stars lie at $M_V \sim +1$ (Perryman et al. 1995).

Note that the stars may be found above the Zero Age HB (ZAHB) because of evolution. However, the evolutionary models also show that the region occupied by such stars above the ZAHB is rather narrow, because once the stars have slowly brightened by about 0.5 mag they will evolve away from the HB quite fast.

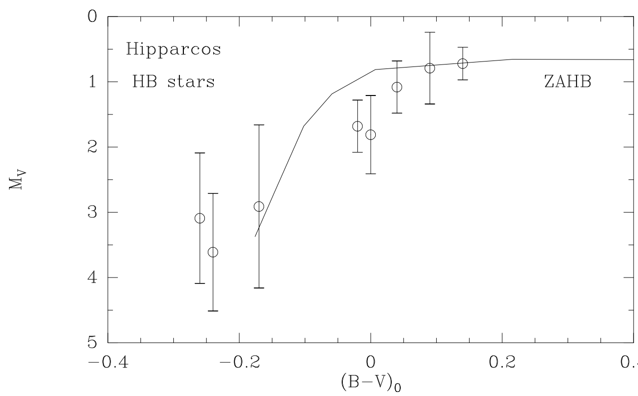

Fig. 1. In this colour magnitude diagram the Hipparcos-based absolute magnitudes define for the first time the location of the horizontal branch for field stars of the Milky Way. The location of the theoretical Zero-Age HB according to Dorman's (1992) model ([Fe/H]= −1.03, Y_{HB} = 0.252) is shown as a solid line

4. Luminosity, temperature, gravity

The luminosity, L_{HB}, is a further basic parameter of a star. It is defined by the amount of energy produced in nuclear fusion and therefore reflects the internal constitution of the stars. We have determined the extinction corrected apparent luminosity, l_{HB}, from spectrophotometry in the visual and in the satellite UV. The UV data are from the IUE (see e.g. Huenemoerder et al. 1984; [HBC]), visual data from various sources, as indicated with Table 2. The correction for the effect of interstellar extinction, A_λ (from Savage & Mathis 1979), is applied in two steps; first the spectral energy distribution was corrected for the reddening $E(\lambda - V)$, and then, after the spectral integration, the appropriate factor A_V was included. The spectral integration has an accuracy of 0.02 dex, ignoring (very small) possible systematic errors in the calibration of the input data. We note that for the HB stars the largest contribution to l_{HB} comes from the spectral range between 3500 and 5000 Å, for the sdB stars from the IUE spectral domain. The extinction values normally are accurate to 0.02 mag, which adds 0.025 dex to the error budget in l_{HB}. The total maximum uncertainty in l_{HB} is therefore 0.04 dex.

The effective temperature, T_{eff}, can be found from photometry or from a comparison of the spectral energy distribution with models. The data used and their sources are given in Table 2. Errors in T_{eff} normally are $\leq$5%.

A T_{eff},log g combination (normally a range of pairs is possible) follows from a fit of the observed shape of the Balmer lines to theoretical profiles (see, e.g., de Boer et al. 1995). In log g the errors are of the order of 0.2 dex.

In Fig. 2 we show T_{eff} vs. log g for the stars (for sources see Tab. 2). They tend to lie somewhat above the ZAHB. This effect is known from several studies of field horizontal-branch like stars (Moehler et al. 1990; Theissen et al. 1993; Schmidt et al. 1996).

Table 2. HB star parameters

Name	$\log l_{\mathrm{HB}}$[I] (cgs)	source	$\log L_{\mathrm{HB}}$ ($L_\odot$)	T_{eff} (K)	$\log g$ (cgs)	source[II]	Δ ($\log g/T_{\mathrm{eff}}{}^4$)[III]	$\log M_{\mathrm{HB}}$	$\Delta \log M_{\mathrm{HB}}$	M_{HB} ($M_\odot$)
CD −38 222	−7.70:	b,r	1.82:	28200	5.5	g	0.11	+0.20	0.61	1.58
HD 4539	−7.65:	b,r	1.51:	26000	5.43	h,l	0.04	−0.15	0.40	0.71
HD 86986	−7.768	a,c	1.57	7900	3.1	f,k,p	0.10	−0.32	0.32	0.48
HD 109995	−7.666	a,c	1.45	8300	3.15	f,k,n	0.20	−0.44	0.36	0.37
HD 130095	−7.679	a,c	1.28	8800	3.4	f,k,p,s	0.15	−0.49	0.31	0.32
HD 139961	−7.788	a,s	1.39	8750	3.3	k,s	0.20	−0.48	0.44	0.33
HD 161817	−7.402	a,c	1.58	7500	2.95	f,k,n,q	0.05	−0.37	0.15	0.42
HD 205805	−7.60:	b,r	1.75:	25000	5.0	h	0.10	−0.23	0.45	0.59

I) apparent luminosity l_{HB}, corrected for extinction A_λ (see Sect. 3); for CD −38 222, HD 4539 and 205805 no contribution below 1100 Å was included; it may amount to 20% extra.
a = UV from IUE (see HBC); b = UV from IUE ULD-archive; c = scanner, Philip & Hayes (1983)
II) T_{eff} and $\log g$ are best averages from the cited literature: f = Hayes & Philip (1988); g = Heber et al. (1984); h = Heber & Langhans (1986); k = HBC; l = Saffer et al. (1994); n = Böhm-Vitense (1980); p = Adelman & Philip (1990); q = Adelman & Hill (1987); r = Hauck & Mermilliod (1980); s = Schmidt et al. (1996)
III) see Sect. 5

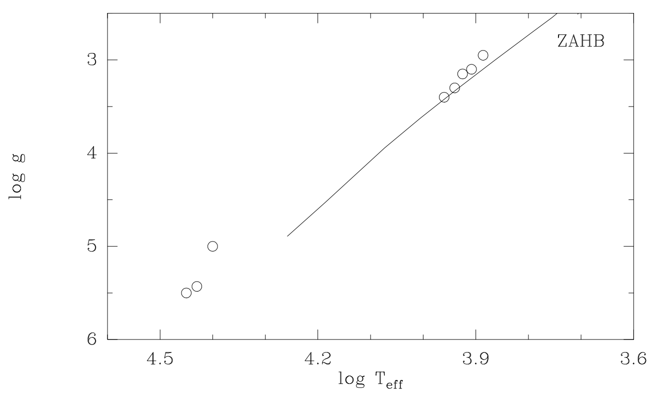

Fig. 2. The location of the HB stars studied is shown in the Hertzsprung-Russell diagram. The ZAHB is as in Fig. 1

5. From parallax, photometry, and spectra to masses

The parameters characterising a star (luminosity L, mass M, radius R, surface temperature T_{eff}, and gravity $\log g$) form a fully defined set. If the parameters can be determined independently of each other, this set may serve to check the consistency of all values.

These parameters have the well defined relations

$$L = 4\pi R^2 \times \sigma T_{\mathrm{eff}}^4 \quad \text{and} \quad g = G \times M/R^2 \tag{1}$$

which can be conveniently combined into

$$\log\left(\frac{M_{\mathrm{HB}}}{M_\odot}\right) = \log g_{\mathrm{HB}} - 4\log T_{\mathrm{HB}} + \log l_{\mathrm{HB}} + 2\log d + 15.11 \tag{2}$$

where l_{HB} is the integral of the extinction corrected spectral energy distribution as measured at the Earth (the apparent luminosity) and d is the distance of the star in pc (the parallax $\pi = 1/d$, with π in arcsec). The numerical constant 15.11 comes from

$$\log 4\pi + 2\log(3.09 \times 10^{18}) - \log L_\odot + 4\log T_\odot - \log g_\odot \tag{3}$$

with the solar values $L_\odot = 3.85 \times 10^{33}$ erg s^{-1}, $T_\odot$ = 5800 K, and $\log g_\odot$ = 4.44 in cgs units.

The T_{eff} and $\log g$ values require some extra discussion. They are derived as a pair from Balmer-profile fitting, so their errors are interrelated, as follows. If a slightly larger T_{eff} would have been chosen within the permitted range, a slightly larger $\log g$ would have been required. Since in the equation the difference $\log g - 4\log T$ enters, the total error in $\log (g/T_{\mathrm{eff}}{}^4)$ is quite smaller than the sum of the individual errors. Going back to the original data where possible, we have determined the true error $\Delta \log (g/T_{\mathrm{eff}}{}^4)$, and give those values in Table 2.

Inserting all the values into the equations readily leads to the value for the mass of the HB stars. The propagated uncertainties in the masses ($\Delta \log M_{\mathrm{HB}}$) amount to 0.15 to 0.6. These results are collected in Table 2.

The masses derived for the 5 cool HB stars all lie in the vicinity of 0.4 $M_\odot$ with a rather small spread (the arithmetic average is 0.38 $\pm$0.07 $M_\odot$). This value is surprisingly low. Since the mass of HB-like stars is expected to be related with temperature, we show in Fig. 3 the mass of the stars against T_{eff}.

6. Which parameter is the culprit?

The mass for the HBA stars is with $\sim$0.4 $M_\odot$ clearly below the mass predicted by theories about the structure of HB-like stars. This result is very similar to that found for the HB-like stars in globular clusters (de Boer et al. 1995; Moehler et al. 1995; Moehler et al. 1996). On the other hand, the 3 sdB stars (with T_{eff} near 25000K) have a mass near or above that of the models, but with large uncertainties. As with the globular cluster stars, the cooler ones deviate from the theoretical expectation.

The internal errors have well understood sources (see Sect. 4). The total propagated uncertainty for the cool HB stars

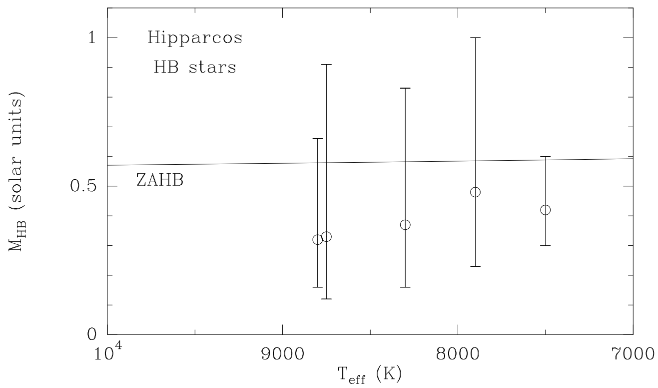

Fig. 3. The mass of the cool HB stars is shown in relation with T_{eff}. The data points lie below the ZAHB from the models

is 0.15 to 0.44 dex, represented by the error bars in Fig. 3. The individual errors are dominated by the errors in log $(g/T_{\text{eff}}{}^4)$ and in π, by about equal amounts. However, the spread in the values themselves is small, so that the stars investigated basically give the same result and mutually confirm the low mass values.

In order to assess the reliability of the results we will summarise the effects of the various parameters.

Parallaxes: systematic errors are very small (Sect. 2).

Visual magnitudes: V is accurate; values of M_V derived agree well with the models (Fig. 1).

Luminosities: systematic errors in the integrated spectral energy distribution are very small (see Sect. 4).

Temperature: systematic errors are very unlikely since the overall spectral energy distribution can be fitted well to model calculations for large ranges of type of star.

Gravities: systematic errors are hard to assess. On the one hand, the gravities for the hot stars seem to be well behaved in connection with other stellar parameters. On the other hand, the gravities for cooler HB stars have been found to be too low before, both in the field stars and in the globular cluster stars (Moehler et al. 1990, 1995). Lanz et al. (1995) suggest that fully blanketed non LTE models alleviate a similar problem for hot Pop.I stars.

7. Conclusions

Hipparcos parallaxes allowed to calibrate HB stars completely. Using all available parameters, both the gravities and the masses are found to be different than atmosphere and evolution models predict. Most likely the cause for the discrepancy lies in problems with the derivation of log g from Balmer profiles for stars in the indicated temperature range. This conclusion was also reached by de Boer et al. (1995) for the globular cluster stars. We refer to that paper for a detailed discussion of the consequences when systematic changes in various parameters are introduced. For the clusters the problem might be alleviated to some extent when the distance scale is changed, but this option is for the Hipparcos parallaxes not viable. An investigation of the gravity effects in relation with HB stars must be the next step in HB star research.

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